CONSTANT TEMPERATURE CREEP STUDIES OF SOME SIMPLE POLYMERIC COMPOSITES

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SOME SIMPLE POLYMERIC COMPOSITES

by

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ABSTRACT

An investiagtion of uniaxial creep in simple synthetic composites of polyethylene and polypropylene was made to determine the parametric behavior and interrelation of each component by varying the relative volume and interfacial contact area. A mathematical model was developed and used to predict the experimental behavior which was determined by least squares fitting of the data. A digital computer was used in the analysis and good correlation between the experimental measurements and theoretical predictions was obtained. Included is a report of the design and construction of equipment for theoretically meaningful viscoelastic measurements.

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NOTATION

σ	Nominal stress
σ_o	Initial stress
$\dot{\sigma}$	Stress rate
ε	Nominal strain
$\dot{\varepsilon}$	Strain rate
δ	Elongation
ΔL	Change in length
L	Length
L_o	Initial length
P	Force
A	Cross sectional area
G	Modulus in shear
E	Modulus in tension
η	Coefficient of viscosity
τ	Time constant
t	Time
PE	Polyethylene
PP	Polypropylene

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1. Introduction

The rapid expansion of today's advanced technology is evidenced in the literature by the large number of publications related to the design, fabrication, testing and usage of composite materials. The use of composites as a structural material is not new but the related technology is just now beginning to grow. Almost all of the experimental work on the properties of composites has been performed in direct response to the immediate technological needs. As a result, very little basic research has been reported.

One of the definite voids in the knowledge of the behavior of composite materials is that which is associated with its visoelastic properties. [5, 7, 14] * This viscoelastic behavior is evidenced in the creep and stress relaxation mechanisms of the composite and needs to be related to the interaction between the basic components of the composite.

The primary purpose of this study was to investigate the constant load creep behavior of a simple synthetic composite of known structure. Measurements were obtained at a temperature of 23±1 degree C and a relative humidity of 50 ± 2 % in accordance with ASTM Standards. [15] A comparison of the behavior of the variously constructed composites with that of the parent materials was attempted by least squares fitting of the data using standard digital computer techniques and graphical analysis.

Appendix C is a report of the design and establishment of a Laboratory for the purpose of making these measurements.

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*Numbers in brackets refer to Articles in the Bibliography.

$$\varepsilon = \frac{\sigma_0}{E_0} + \sum_{i=1}^{n} \frac{\sigma_0}{E_i}\left[1 - \exp\left(-\frac{t}{\tau_i}\right)\right] + \frac{\sigma_0}{\eta(t)}\, t$$

Where

$$\tau_i = \eta_i / E_i$$

$$\sigma_0 = \text{initial stress.}$$

Simplifying the system further by letting n = 1;

$$\varepsilon = \frac{\sigma_0}{E_0} + \frac{\sigma_0}{E_1}\left[1 - \exp\left(-\frac{t}{\tau_1}\right)\right] + \frac{\sigma_0}{\eta}\, t .$$

The single element Voigt Model or a suitable modification thereof can easily be used to describe the creep behavior of a material in response to a given initial stress σ_0 by superposition of the linear terms in stress and time. Marin [13] has extended these simple relations to provide implicitly for a variety of stress levels and has shown that these relations can be fitted to the actual response of many metallic and polymeric materials. Of various suggestions, the following generalized equation of Marin and Pao [22] seems to have the simplest form and follows the superposition principle quite readily:

$$\varepsilon = \frac{\sigma}{E} + K\sigma^n\left[1 - \exp(-Pt)\right] + B\sigma^m\, t .$$

Figure 9 shows how this equation appears using the superposition principle for one given stress level. Figure 10 is a family of creep curves constructed using Marin's equation for five different stress levels. Such a family has been shown to depict the viscoelastic behavior of a simple polymer quite well.

In addition to its application to the structure for a given stress level, we can apply the above principles to the Generalized Maxwell Model of m elements and obtain an equation which describes

the constant strain behavior (stress relaxation) of a material. The following equation may be obtained:

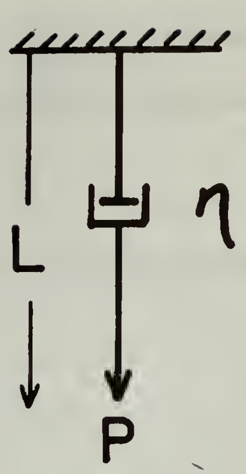
$$\sigma = \varepsilon_o \sum_{i=1}^{m} E_i \exp\left(-\frac{t}{\tau_i}\right)$$

A complete solution of these systems is found in reference [10] .

$$P = GL$$

FIGURE 1

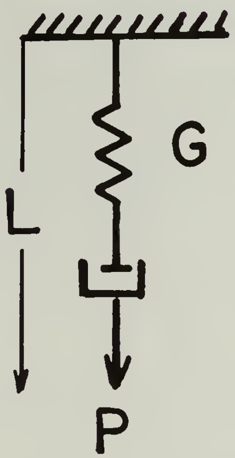
The Hookian Solid



$$P = \eta \dot{L}$$

FIGURE 2

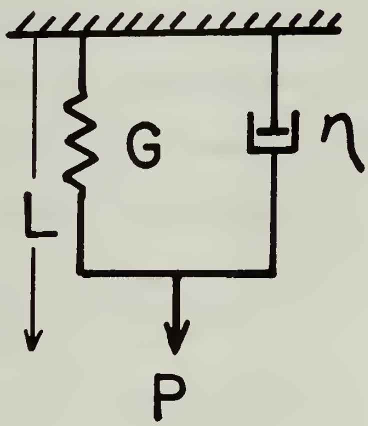
The Newtonian Liquid



$$\dot{L} = \dot{P}/G + P/\eta$$

FIGURE 3

The Maxwell Model



$$P = GL + \eta \dot{L}$$

FIGURE 4

The Kelvin-Voigt Model

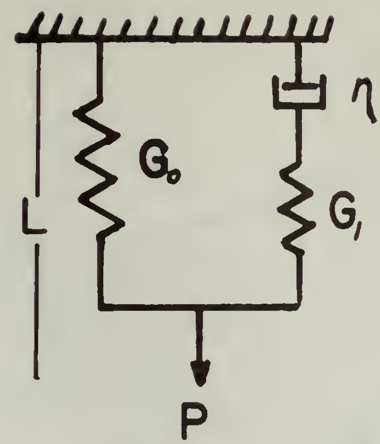


FIGURE 5

The Standard Linear Solid

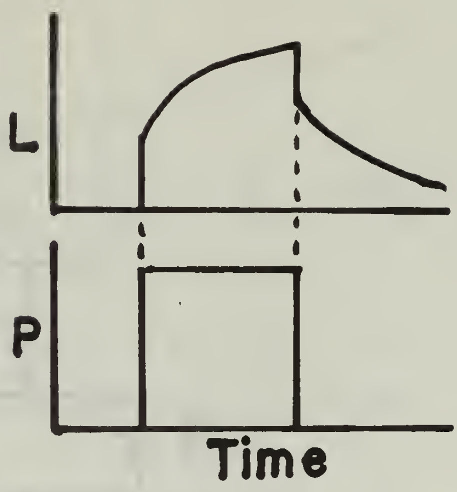


FIGURE 6

Mechanical Behavior of Standard Linear Solid

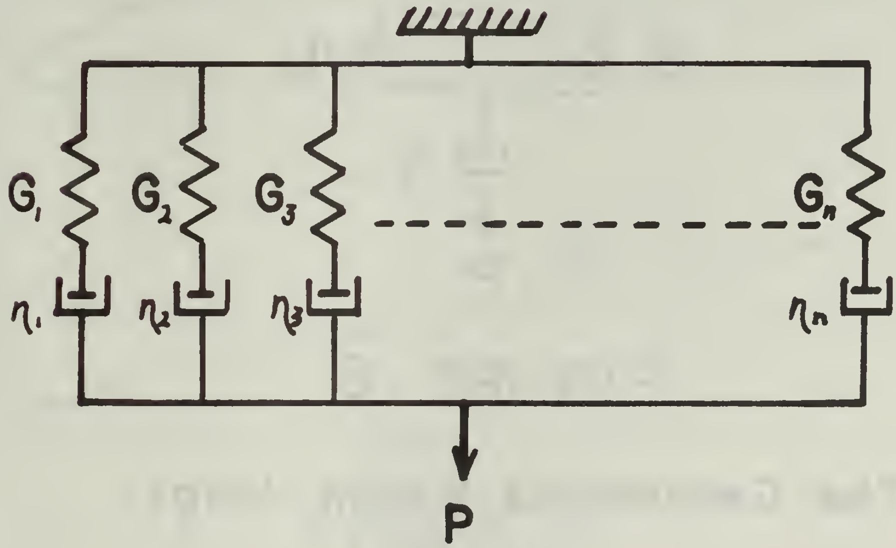


FIGURE 7

The Generalized Maxwell Model

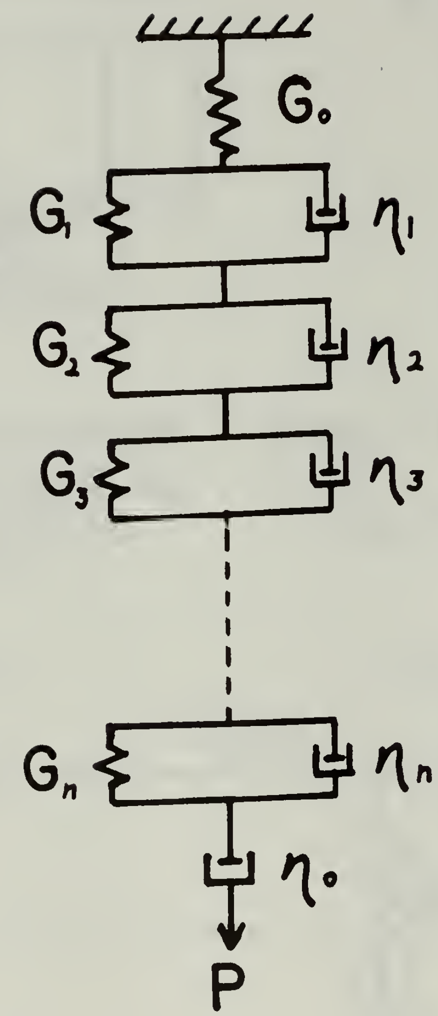


FIGURE 8

The Generalized Kelvin - Voigt Model

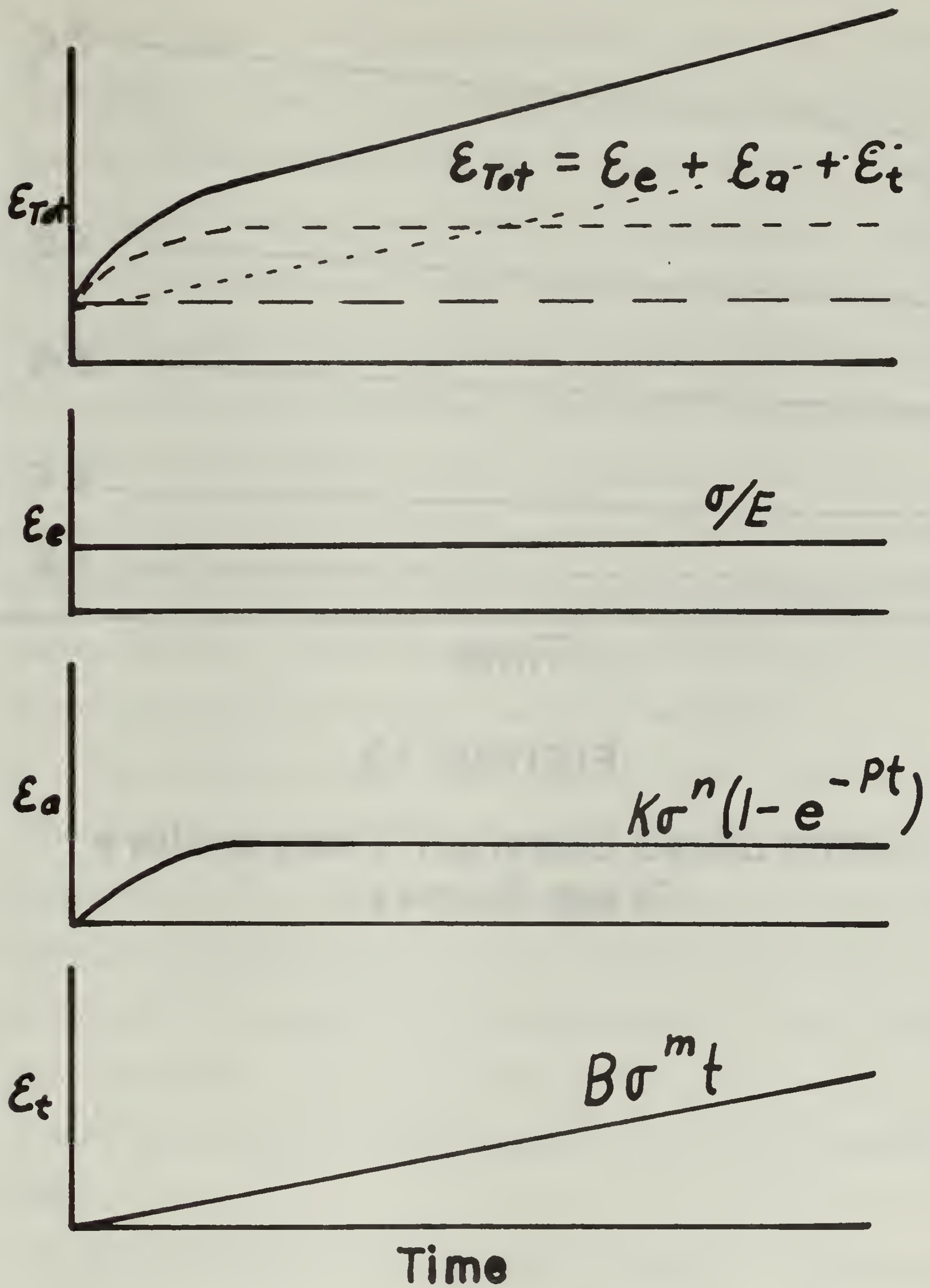


FIGURE 9

Superposition of Time Dependent and Time Independent Elongations in Creep

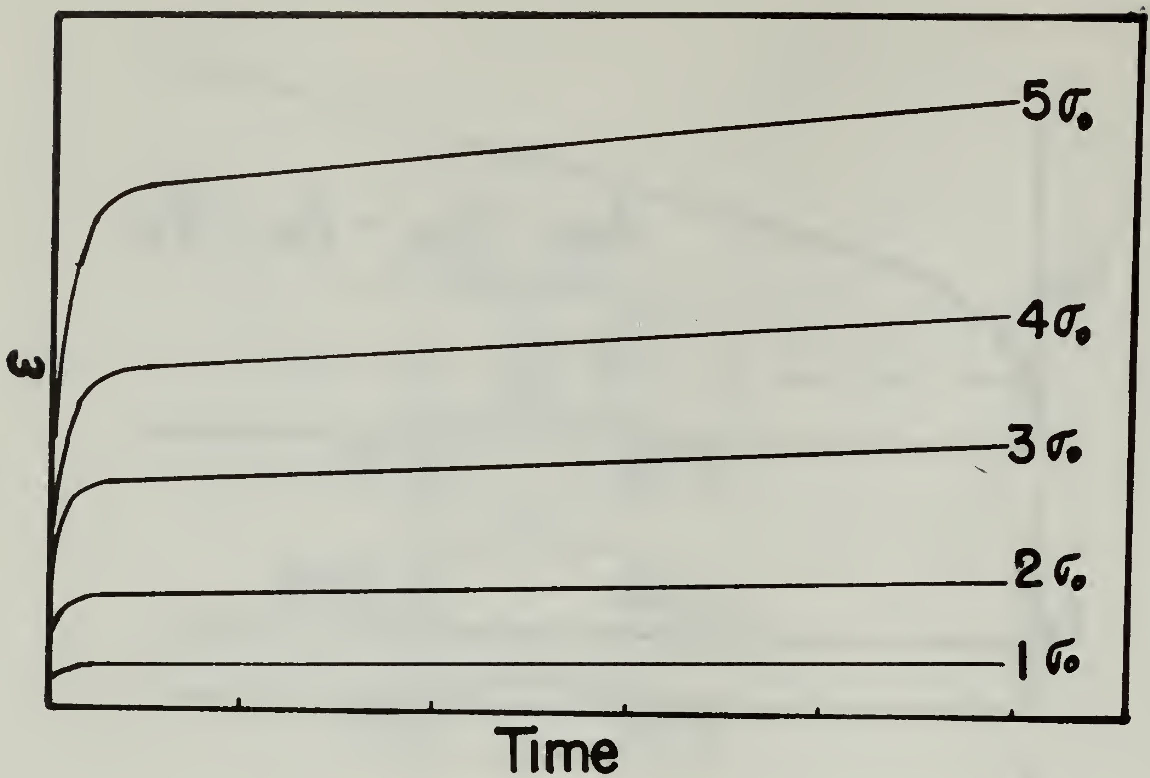


FIGURE 10

Generalized Constant Temperature
Creep Curves

4. Statement of the problem.

The purpose of this study was to investigate the creep behavior of two polymeric materials which were mechanically laminated into a composite structure readily described by simple numbers. A series of constant load machines were used for load application. Linear high density polyethylene and isotactic polypropylene were chosen as the basic materials. Both materials are readily available commercially and both have known composition. Each creeps to a relatively large extent at room temperature using low stresses. Both are crystalline to some degree and their structures may well vary with extension. This property is one which will allow further study of the molecular mechanisms involved. The possible extension of this work is an additional reason for the choice of these particular materials.

The creep measurements were relatively short time tests with an average elapsed time of 100 hours. The variables studied were relative cross-sectional area and the effect of interfacial bonding between the laminates at various stress levels. The data obtained were compiled and fitted to a simplified mathematical model of creep (after Marin) as described above. From this fitted equation, the parameters E, K, n, m, P and B were obtained for each composite and a direct comparison was made.

It was necessary for this study to establish a suitable laboratory for the measurement of creep. This required the installation of temperature and humidity control equipment of sufficient size to maintain the temperature and relative humidity throughout the laboratory. Also, since the obtaining of data is a tedius and time consuming process, a method of recording the data for many units was devised. This equipment is described in Appendix C.

5. The Experiment.

Specimens of linear high density polyethylene and isotactic polypropylene were made with the dimensions of Figure 11. The extruded sheet material was cut into random rectangles oriented parallel, perpendicular and diagonally to the extrusion direction. These specimens were marked according to location and orientation in the sheet and used in groups for creep measurements. Preliminary experimental work used the phosphor bronze clip extensometers described in Appendix C, but the data reported here was obtained using Tripolitis type extensometers. (See Figs. 12 and 13.) The gauge length for all specimens was two inches and the extensometer could be accurately read to ± 0.0002 inches. Readings of the data were taken at 2, 5, 10, 15, 20, 25, and 30 seconds total elapsed time, thence varying intervals from 10 seconds to 5 minutes in the first 15 minutes, 5 minutes to 15 minutes in the next 30 minutes and 15 minutes to 30 minutes to approximately 4 hours. Various additional readings were taken to sufficiently determine the extension over a range of 90 to 150 hours total elapsed time. An average of 40 data points were taken on the low stress runs and 60 data points on the high stress runs. An example of the data is enclosed in the test program found in Appendix B.

The temperature was maintained at 23 ± 0.8 degrees C throughout the experiment. It is noted that this degree of temperature control was barely adequate for these materials at low stress levels due to the high coefficient of thermal expansion. The relative humidity was not critical due to the nature of the materials but was maintained within the range 48 to 60 %.

Constant load Creep machines (See Appendix C.) with calibrated lever type loading arms and either universal joints or ball and socket

joints above and below the specimen to eliminate any possible torsion or bending of the specimen were utilized.

Initially, many measurements of the creep of single material polyethylene or polypropylene were obtained. The statistical spread of the data was determined to be due largely to the inhomogeneity of the material, and these errors such as measurement errors, errors due to temperature and relative humidity fluctuations and roundoff errors in compiling and processing the data were masked by the statistical spread.

The next series of tests were carried out on two single layers of polyethylene and polypropylene clamped together in parallel with 80 mesh abrasive uniformly spread throughout the interfacial area. These clamps, shown in Figure 14, were placed outside the gauge length to insure the uniform extension of the material between the clamps. Periodic tightening of these outside clamps prevented any relative motion or slippage between the layers. Further tests in this series were made using two polyethylene and one polypropylene or two polypropylene and one polyethylene layers clamped in parallel as in the previous case.

The second series of tests was run on singly layered polyethylene and polypropylene composites using the previously mentioned outside clamps and auxiliary clamps within the gauge length (See Figs. 14 and 15.) to ensure that contact existed between the materials used. The auxiliary clamps within the gauge length were attached in such a way that only a line of contact was made between the clamp and the specimen, thereby eliminating any restraint on the individual fibers of the material except at the line of contact. The imbedded 80 mesh

abrasive served to increase the interfacial contact at points in the vicinity of the clamps by a pinning action. A series of 1, 2, 3, and 4 of these auxiliary clamps were used on the two layer composites at different stress levels to determine the effect of an interface and any shear stresses between the laminates. (See Fig. 16.) All runs were made at initial stresses of 500, 750, 1000, 1250, 1500 and 1750 psi. These particular stress levels were chosen since polyethylene enters the tertiary creep region above 1750 psi. Polyethylene does not enter this region until above 3000 psi but no correlation of the creep due to the polyethylene component is possible at stresses of this magnitude.

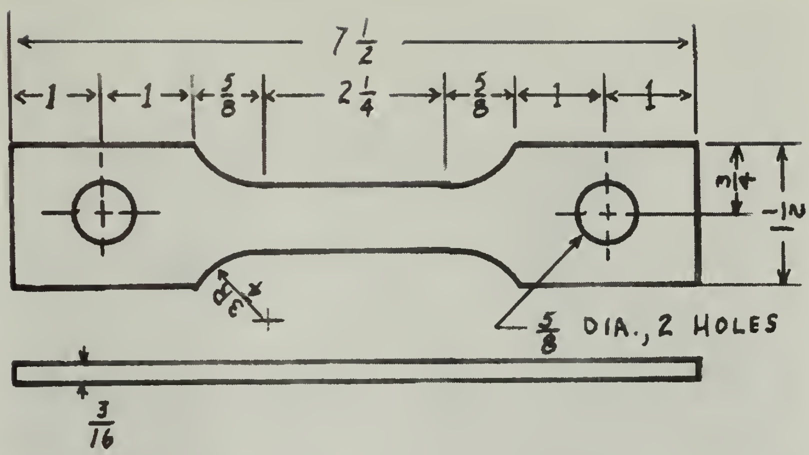


FIGURE 11 CREEP SPECIMEN

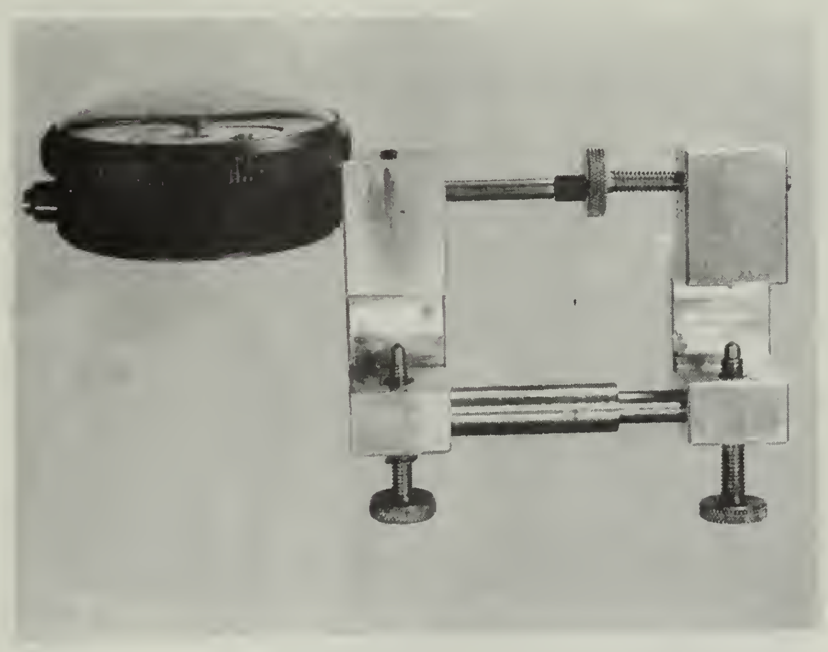


FIGURE 12 TRIPOLITIS EXTENSOMETER

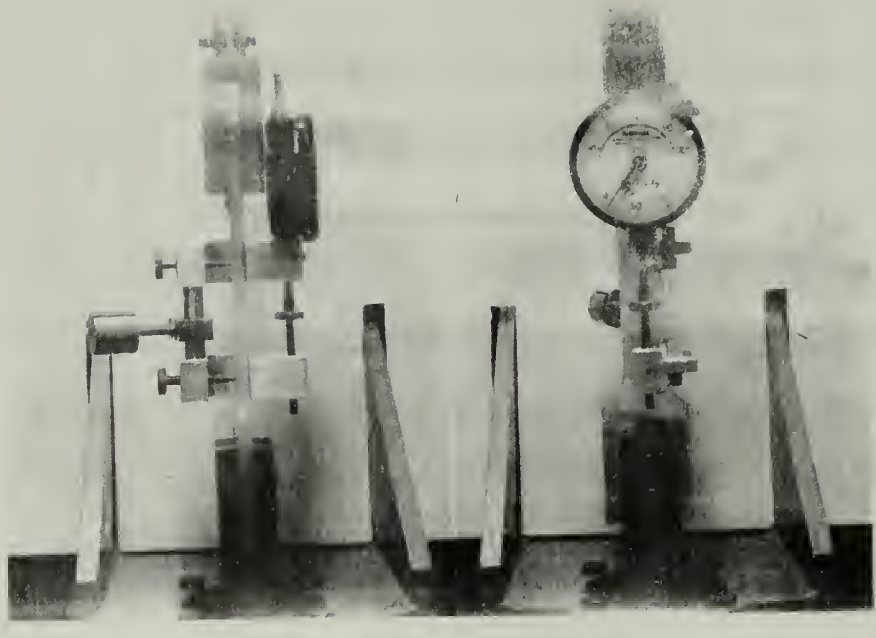


FIGURE 13 TRIPOLITIS EXTENSOMETER
ATTACHED TO SINGLE SPECIMEN

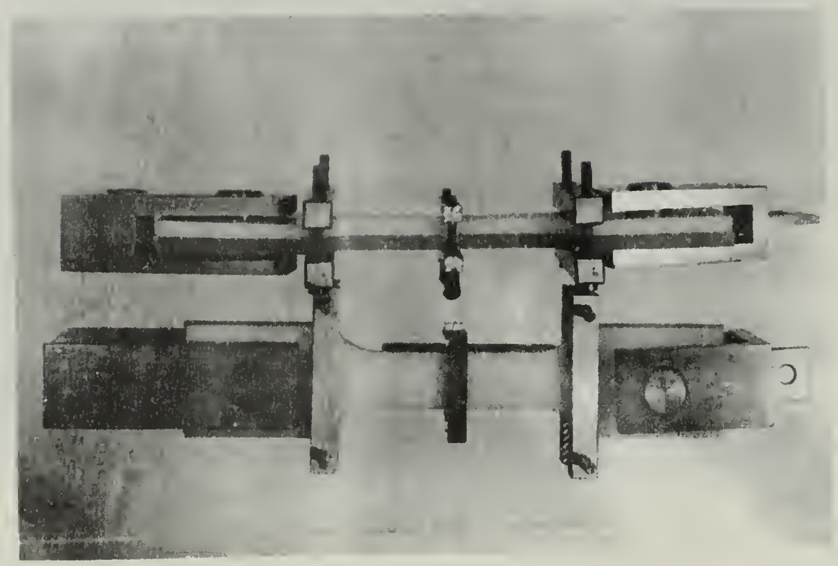


FIGURE 14 PE/PP COMPOSITE WITH CLAMPS

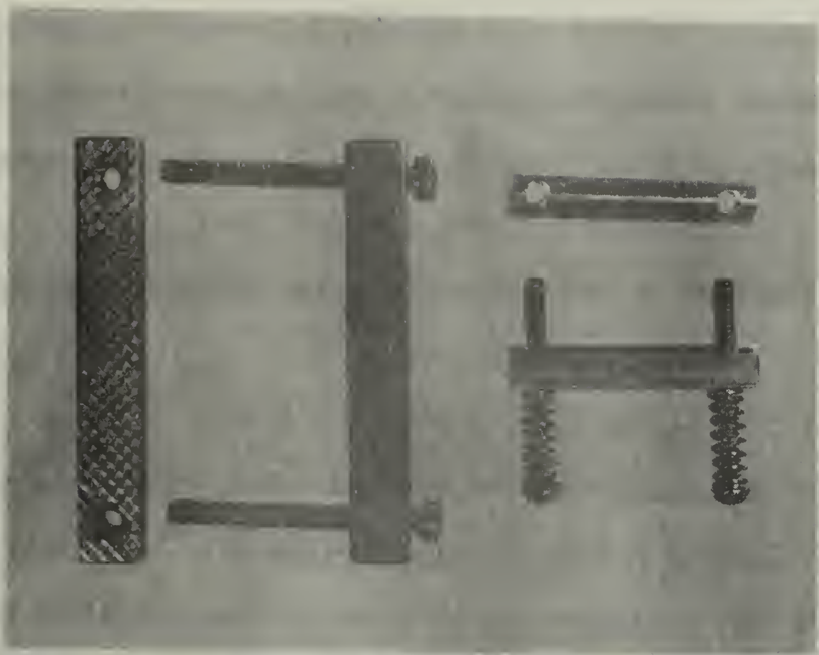


FIGURE 15 CLAMPS USED INSIDE & OUTSIDE GAUGE

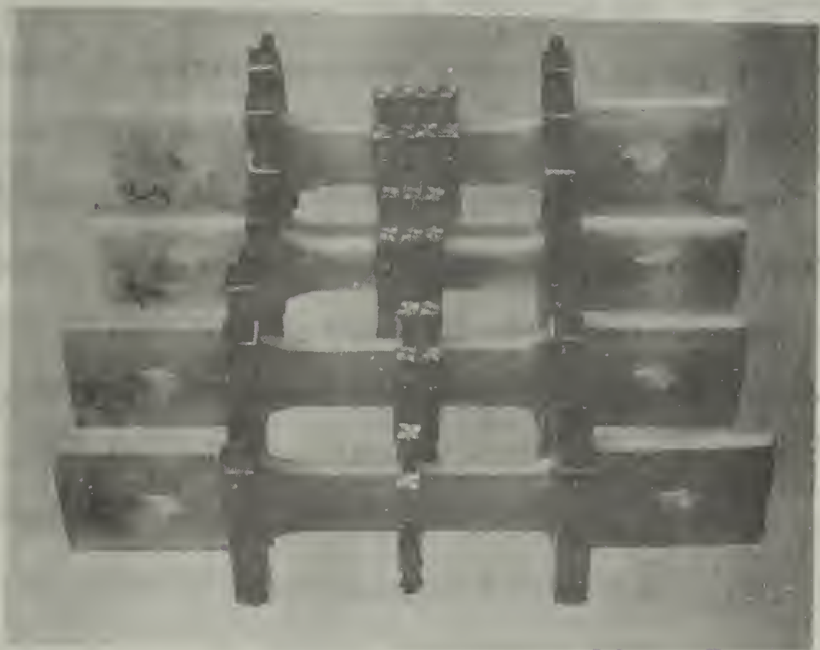


FIGURE 16 PE/PP COMPOSITE WITH 1,2,3&4 AUX. CLAMPS

6. Analysis of the data.

Creep data in the form of elongation ΔL versus time were obtained for all composite specimens studied. The data were punched on cards and placed in the digital computer via the first program in Appendix B. The output of this program included the input data, the calculated stress, the fraction of each component of the specimen, and the parameters A_i (i = 1,2,3,4) of the equation:

$$\Delta L = A_1 + A_2(1 - \exp(-A_3 t)) + A_4 t$$

for which the parameters A_i correspond with those of Marin's equation:

$$\varepsilon = \frac{1}{L_o}\left(\frac{\sigma}{E} + K\sigma^n(1 - \exp(-Pt)) + B\sigma^m t\right).$$

Also included was the difference or error between the fitted equation and the input data points and an estimate of the error in the parameters A_i. Appendix A contains a tabulated compilation of the parameters A_i for all of the specimens investigated.

The second computer program in Appendix B served to compare the input data with the fitted parameters. It was also a very good method of checking the accuracy of the punched data since any gross errors could easily be picked up. Figure 17 is a sample of the output. All data points cannot be shown here since the program used to draw the graph is limited to 30 data points. The continuous curves are drawn using the fitted parameters found by least squaring the data. Although an exact fit is not obtained, the fit is close enough to obtain sufficient information to make a comparison of the effect of relative cross-sectional areas and interfacial contact between the laminates.

Plots of A_1 through A_4 versus stress for single unlayered polyethylene and polypropylene specimens are seen in Figures 18 through 21. Note the statistical spread of data, especially for A_3 versus stress.

Figures 22 through 25 serve as a comparison of the parameters A_i for a simple composite of 50 % polyethylene and 50 % polypropylene. The only clamped areas were outside the gauge length. In addition to these points for the composites, curves for 100 % polyethylene and 100 % polypropylene are included.

From Figure 24 it is apparent that the elastic term of Marin's equation ($\sigma/E = A_1 L_o$) is not linear in stress. Figure 26 is a log-log plot of A_1 versus stress for simple polyethylene and simple polypropylene specimens. The slope is 1.3, indicating that the elastic deformation is in fact dependent on stress to the 1.3 power. Many other materials possess similar nonlinearity and this result is not surprising. Similiarly, a log-log plot of A_2 and A_4 versus stress are seen in Figures 27 and 28 respectively. The slope of the graphs are 2.0 and corresponds to the value of n and m in the equalities ($A_2 = (1/L_o)$ $(K\sigma^n)$) and ($A_4 = (1/L_o)$ $(B\sigma^m)$). These same values of n and m were also obtained from the data on the composite structures. The term A_3, which corresponds to a relaxation time constant, is apparently independent of stress. However, the time scale needed for creep measurements makes it difficult to determine such relaxation time constants accurately. The magnitude of the fitted parameter was found to be 1.5 $hr.^{-1}$ for polyethylene and 0.8 $hr.^{-1}$ for polypropylene.

Figures 29 through 32 are similar graphs of the parameters A_i versus stress for triply layered composite specimens. Those composites labeled PE/PP/PE were 67 % polyethylene and 33 % polypropylene and those labeled PP/PE/PP were 67 % polypropylene and 33 % polyethylene. Note the effect of increasing the relative volume (cross-sectional area) of one component relative to the other component. A_1 appears linear with volume for all

stress levels but A_2 and A_4 are nonlinear.

This nonlinear response is consistent with the mathematical model of the composite. Assuming that Marin's equation:

$$\varepsilon = \frac{\sigma}{E} + K\sigma^2\left[1 - \exp(-Pt)\right] + B\sigma^2 t$$

adequately describes the behavior of these composites and that each component carrys its share of the load dependent only on its fractional cross-section, then the following analysis can be used.

Letting a and b denote the relative fraction of component A and B and using subscripts a, b, and ab to identify component A, B, or the composite AB, an appropriate stress analysis of the composite yields Equations 1, 2 and 3.

(1) $a + b = 1$

(2) $\delta_a = \delta_b = \delta_{ab}$ or $\varepsilon_a = \varepsilon_b = \varepsilon_{ab}$

(3) $a\sigma_a + b\sigma_b = \sigma_{ab}$

for time t = 0 in which only the elastic component has a value,

$$\varepsilon_{ab} = \frac{\sigma_{ab}}{E_{ab}} = \frac{\sigma_a}{E_a} = \frac{\sigma_b}{E_b}$$

$$\sigma_a = \left(\frac{E_a}{E_{ab}}\right)\sigma_{ab} \quad \text{and} \quad \sigma_b = \left(\frac{E_b}{E_{ab}}\right)\sigma_{ab}$$

Combining these equations with Equation 3, one gets Equation 4.

(4) $aE_a + bE_b = E_{ab}$

Equation 4 indicates that the elastic deformation for a composite (term E of the viscoelastic equation) should follow a simple addition law. Figure 36 is a plot of observed values for this term versus fraction of polyethylene in the composite, and shows substantial agreement between this theoretical deduction and observed experimental values.

Similarly, for coefficients K and B of the viscoelastic equation, at time $t = 5/A_3$ the term $(1 - \exp(-Pt))$ is substantially unity, and the term $B\sigma^2 t$ is small. Then

$$\varepsilon_a \doteq \frac{\sigma_a}{E_a} + K_a \sigma_a^2$$

$$\varepsilon_b \doteq \frac{\sigma_b}{E_b} + K_b \sigma_b^2$$

$$\varepsilon_{ab} \doteq \frac{\sigma_{ab}}{E_{ab}} + K_{ab}\sigma_{ab}^2.$$

Using Equations 1 and 2 again, one gets

$$K_a \sigma_a^2 = K_{ab}\sigma_{ab}^2 + \left[\frac{\sigma_{ab}}{E_{ab}} - \frac{\sigma_a}{E_a}\right]$$

$$K_b \sigma_b^2 = K_{ab}\sigma_{ab}^2 + \left[\frac{\sigma_{ab}}{E_{ab}} - \frac{\sigma_b}{E_b}\right]$$

from which

$$\sigma_a = \left(\frac{K_{ab}}{K_a}\right)^{\frac{1}{2}} \sigma_{ab} \qquad \text{and} \qquad \sigma_b = \left(\frac{K_{ab}}{K_b}\right)^{\frac{1}{2}} \sigma_{ab}.$$

Again applying Equation 3, one obtains

$$a\left(\frac{K_{ab}}{K_a}\right)^{\frac{1}{2}} \sigma_{ab} + b\left(\frac{K_{ab}}{K_b}\right)^{\frac{1}{2}} \sigma_{ab} = \left(\frac{K_{ab}}{K_{ab}}\right)^{\frac{1}{2}} \sigma_{ab}$$

which is simplified into Equation 5.

$$(5) \quad a\left(\frac{1}{K_a}\right)^{\frac{1}{2}} + b\left(\frac{1}{K_b}\right)^{\frac{1}{2}} = \left(\frac{1}{K_{ab}}\right)^{\frac{1}{2}}$$

Equation 5 indicates that the reciprocal of the square root of coefficient K for the composite should be an addition of volume fraction of its components. Figure 37 is a plot of this item versus volume fraction polyethylene. It verifies this theoretical deduction.

A similar analysis for coefficient B of the viscoelastic equation indicates that for time much greater than $5/A_3$, Equation 6 can be obtained.

$$(6) \quad a\left(\frac{1}{B_a}\right)^{\frac{1}{2}} + b\left(\frac{1}{B_b}\right)^{\frac{1}{2}} = \left(\frac{1}{B_{ab}}\right)^{\frac{1}{2}} .$$

This deduction is verified by experimental values in Figure 38. The excellent agreement between experiment and deductions based on the viscoelastic equation indicate that these composites do behave as the mathematical model predicts.

The relaxation time parameter A_3 (P of the equation) is not so easily checked. However, similar mathematical manipulations starting with the relation $\varepsilon_a + \varepsilon_b = 2\varepsilon_{ab}$ will yield for finite time t;

$$(1 - \exp(-P_a t)) + (1 - \exp(-P_b t)) = 2(1 - \exp(-P_{ab} t)).$$

Expanding the exponential terms in a Taylor's Series and truncating the series after the second term, Equation 7 is obtained.

$$(7) \quad P_{ab} = \frac{P_a + P_b}{2}$$

Therefore, the composite's relaxation time constant is the average of the time constants of each component. The scatter of data pertaining to this relaxation time constant precludes any quantitative check of this result. However, most data points do fall within those of 100% polyethylene and 100% polypropylene as predicted. (See Figures 20, 24 and 31.)

The results of increasing interfacial contact points by placing the auxiliary clamps within the gauge length and using 80 mesh carborundum as a keying material showed no apparent effect in the creep behavior of the 50 % polyethylene - 50 % polypropylene composites. The statistical spread of data does not appear to be affected in any way as may be ascertained from comparing the data in Appendix A. The effect of an increased number of specimens at 1000 and 1500 psi. merely increased the spread of the data without significantly skewing it in any specific direction.

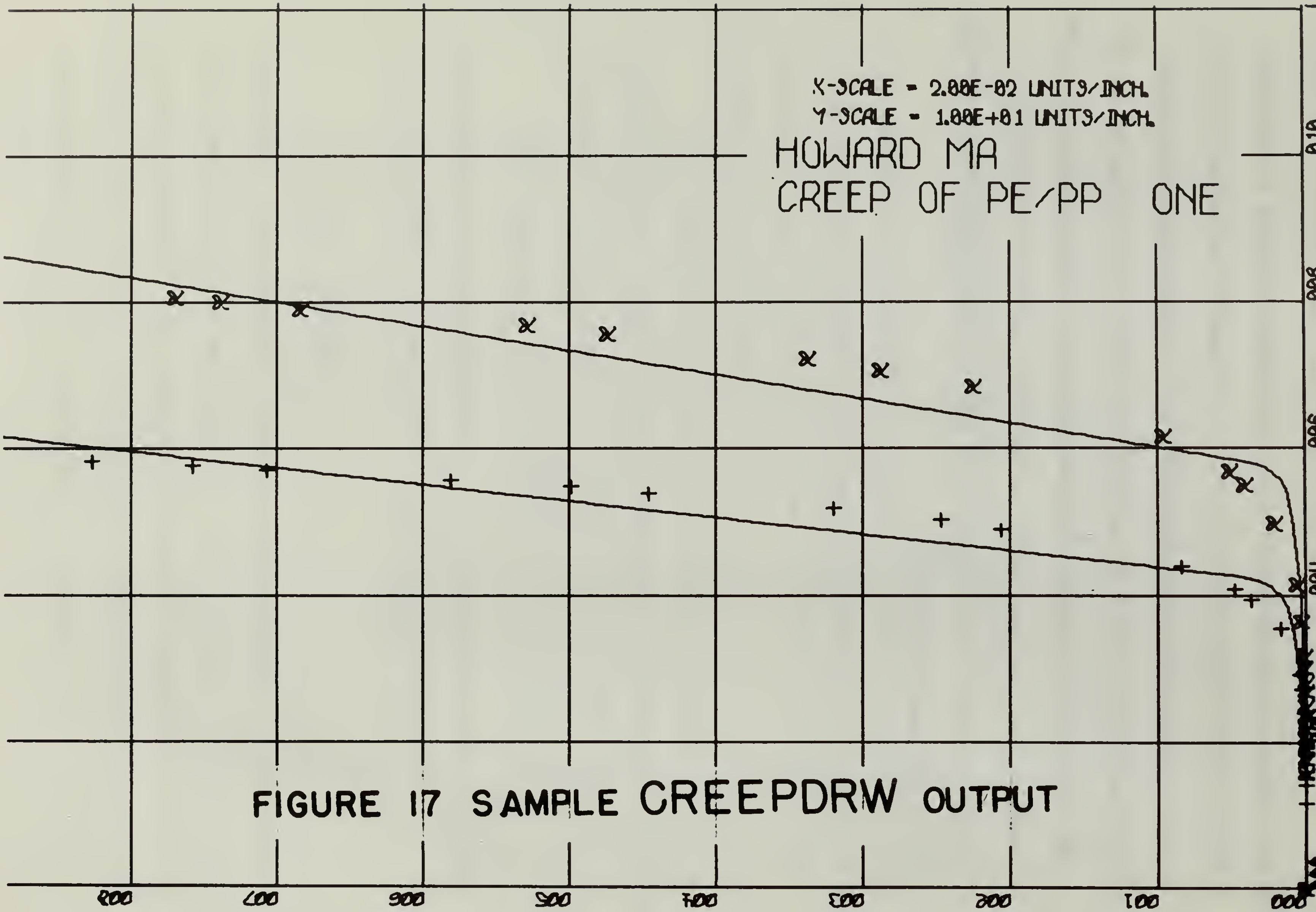


FIGURE 17 SAMPLE CREEPDRW OUTPUT

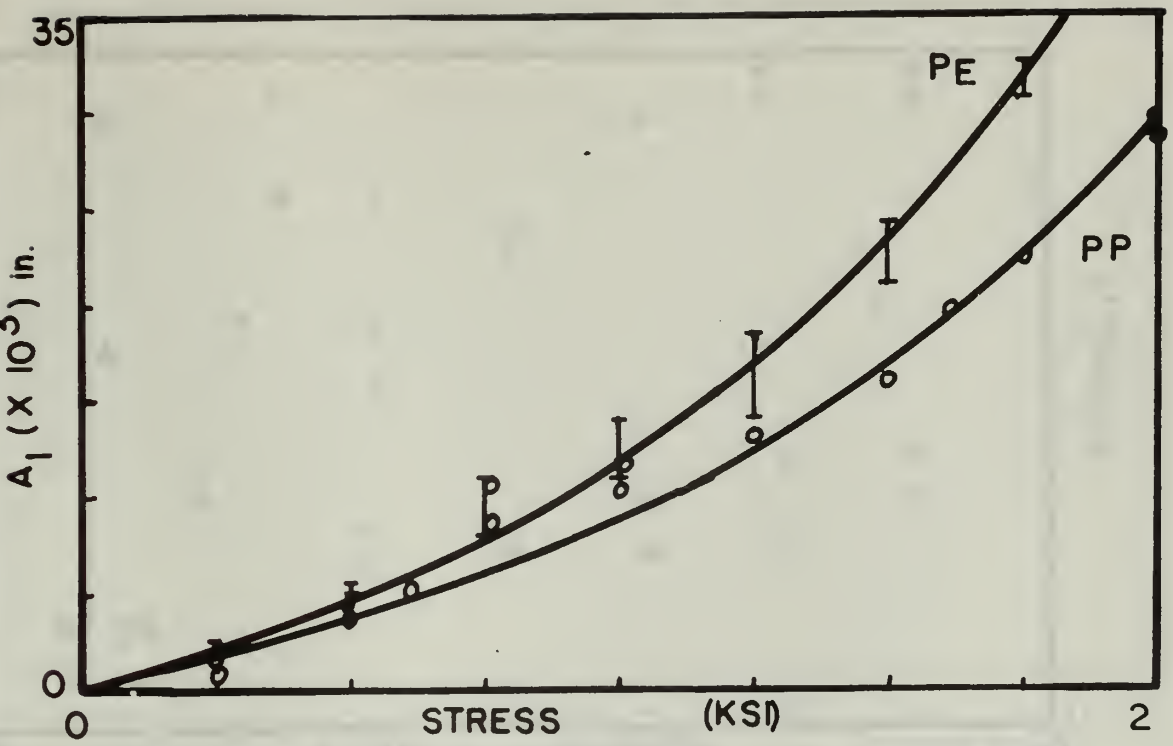


FIGURE 18 PARAMETER A_1 vs. STRESS, SINGLE COMPONENTS

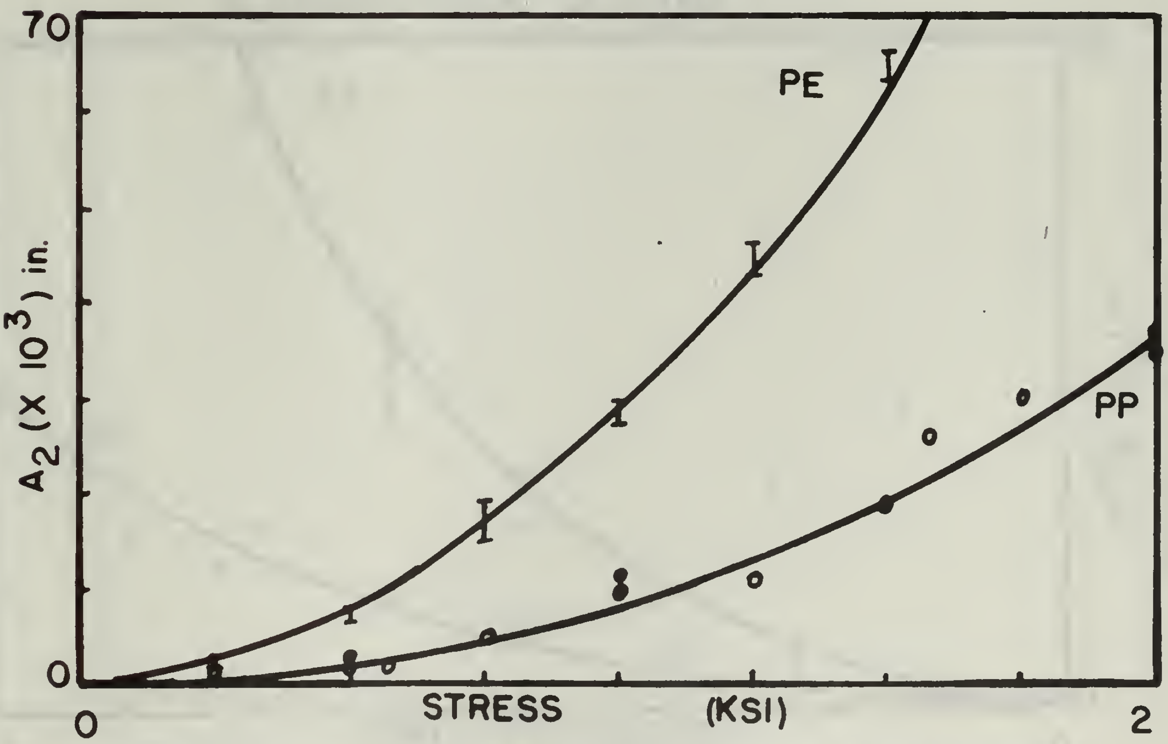


FIGURE 19 PARAMETER A_2 vs. STRESS, SINGLE COMPONENTS

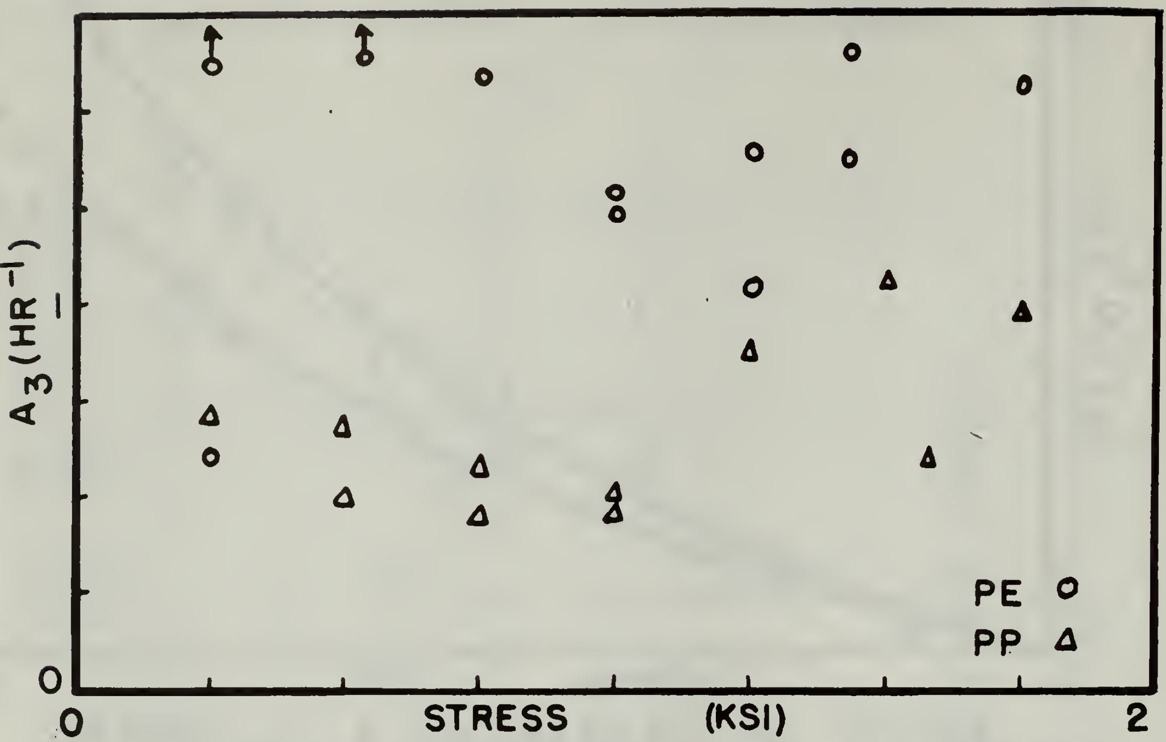


FIGURE 20 PARAMETER A_3 vs. STRESS, SINGLE COMPONENTS

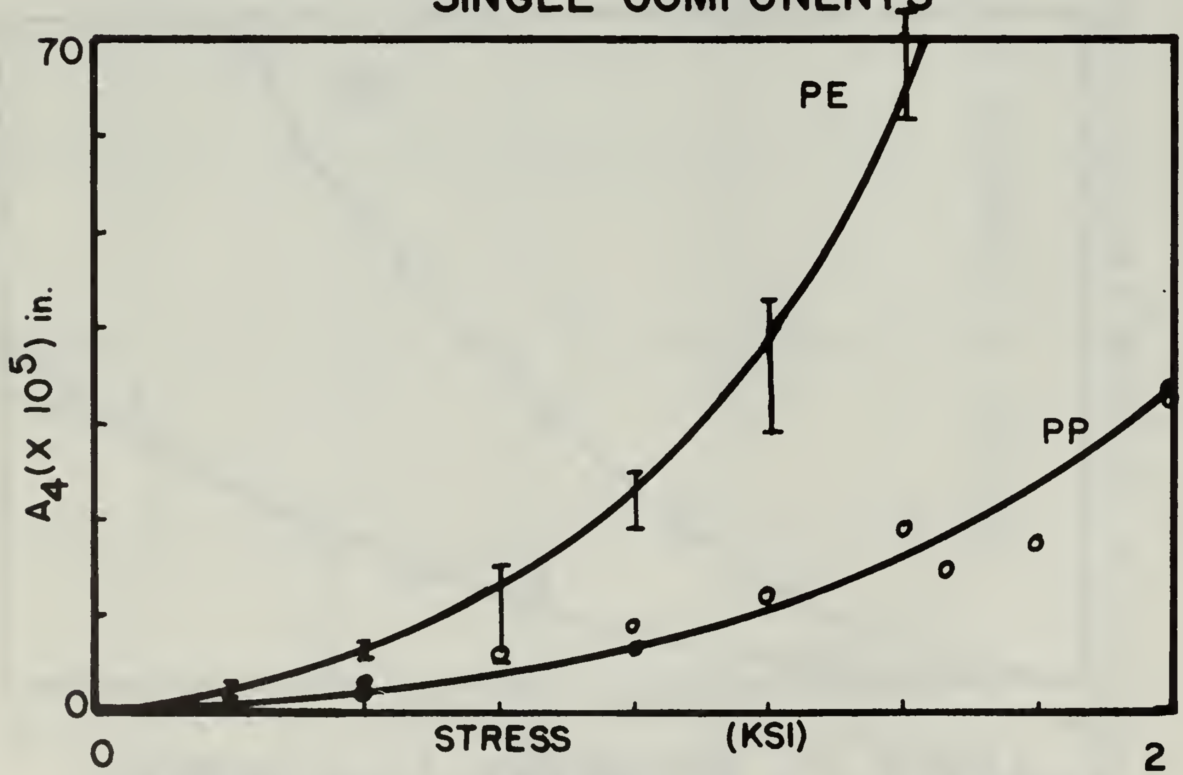


FIGURE 21 PARAMETER A_4 vs. STRESS, SINGLE COMPONENTS

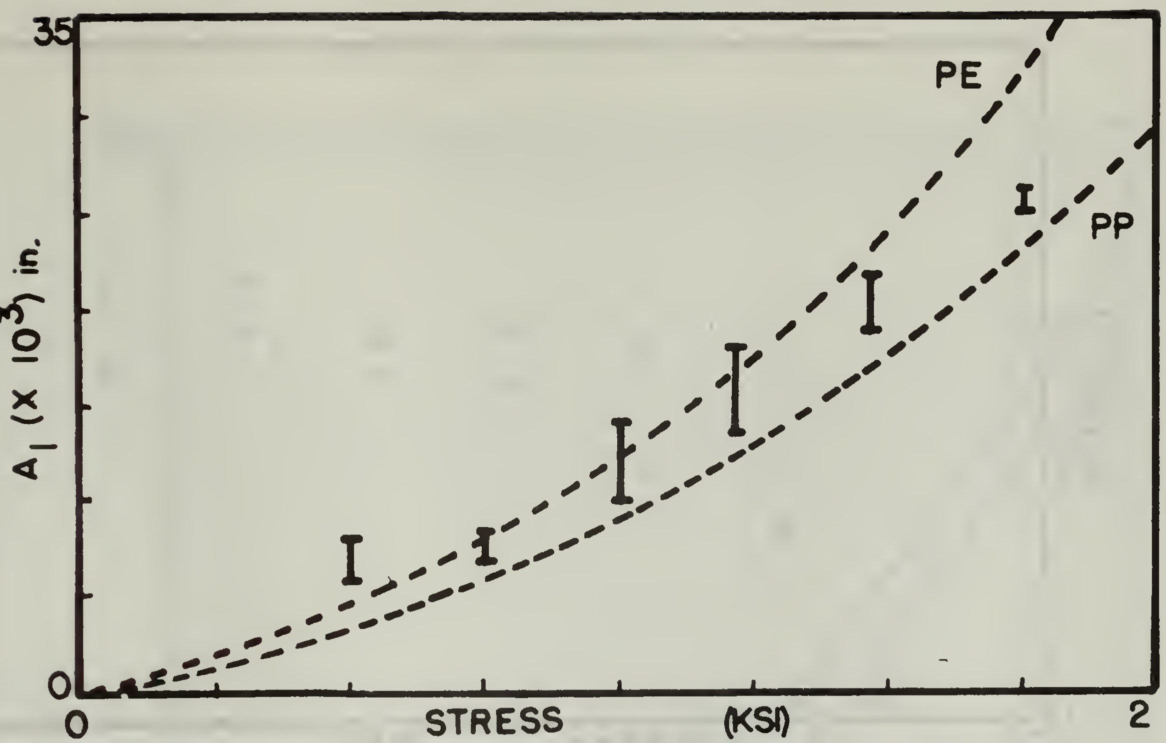


FIGURE 22 PARAMETER A_1 vs. STRESS, 50 % PE- 50 % PP COMPOSITES

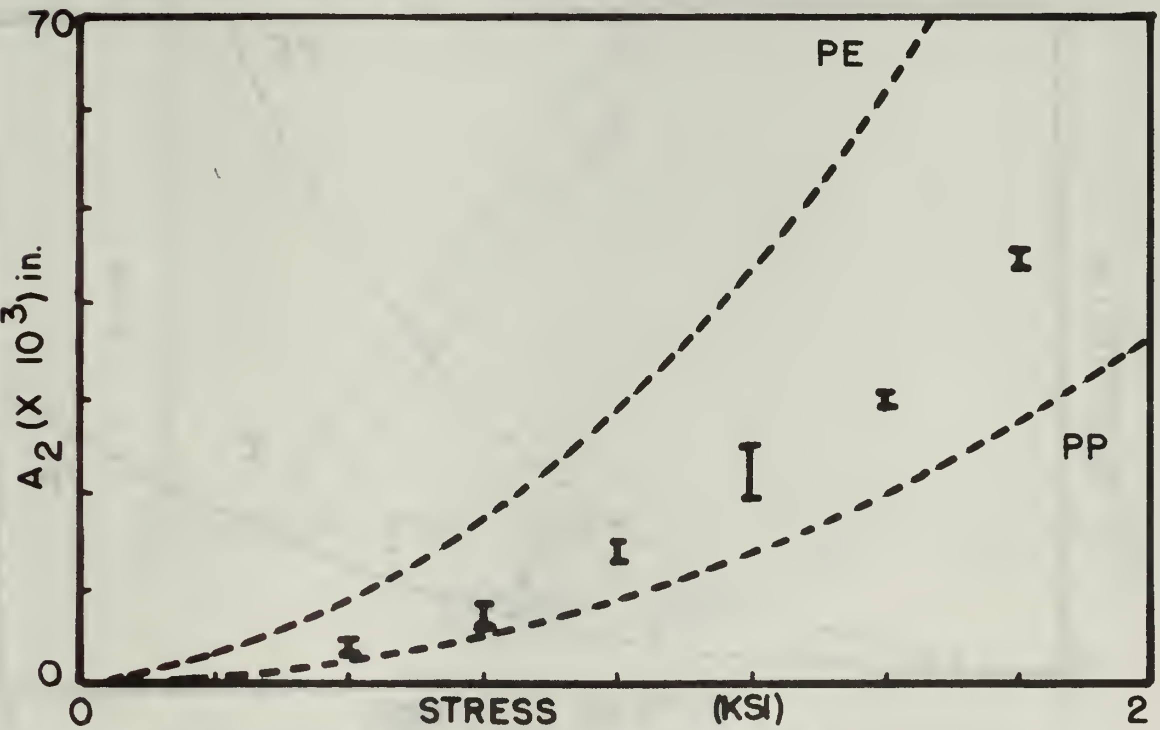


FIGURE 23 PARAMETER A_2 vs. STRESS, 50% PE- 50% PP COMPOSITES

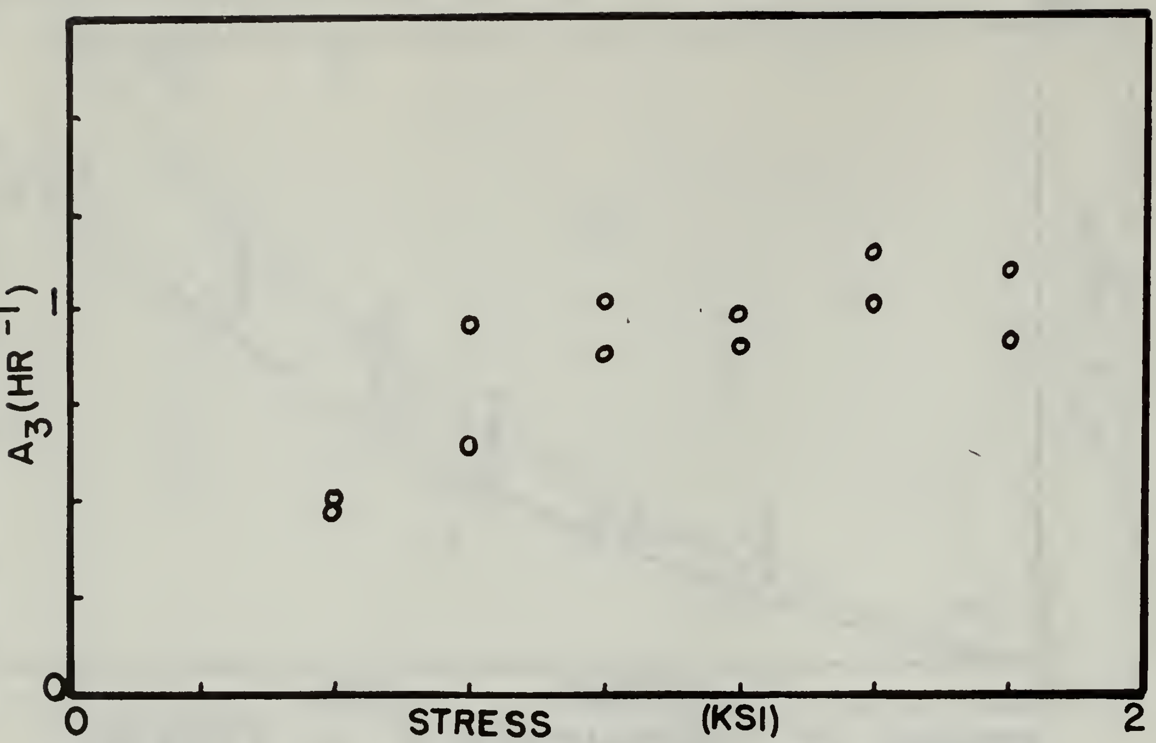


FIGURE 24 PARAMETER A_3 vs. STRESS, 50% PE-50% PP COMPOSITES

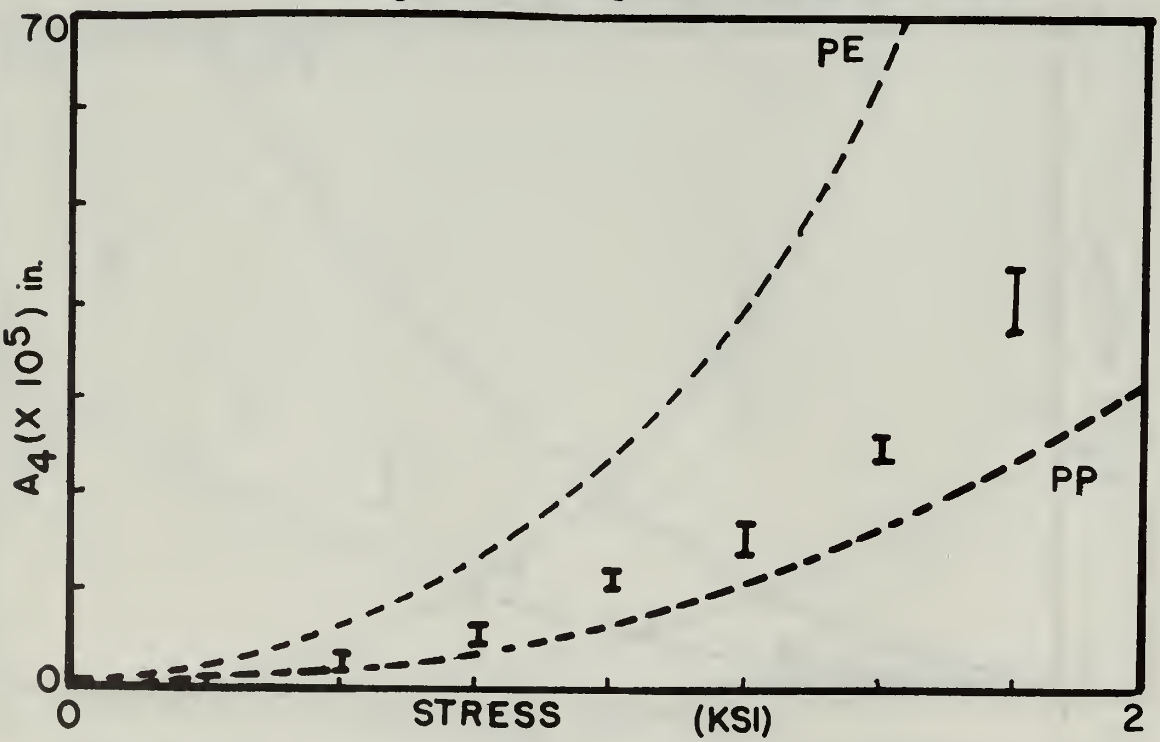


FIGURE 25 PARAMETER A_4 vs. STRESS, 50% PE-50% PP COMPOSITES

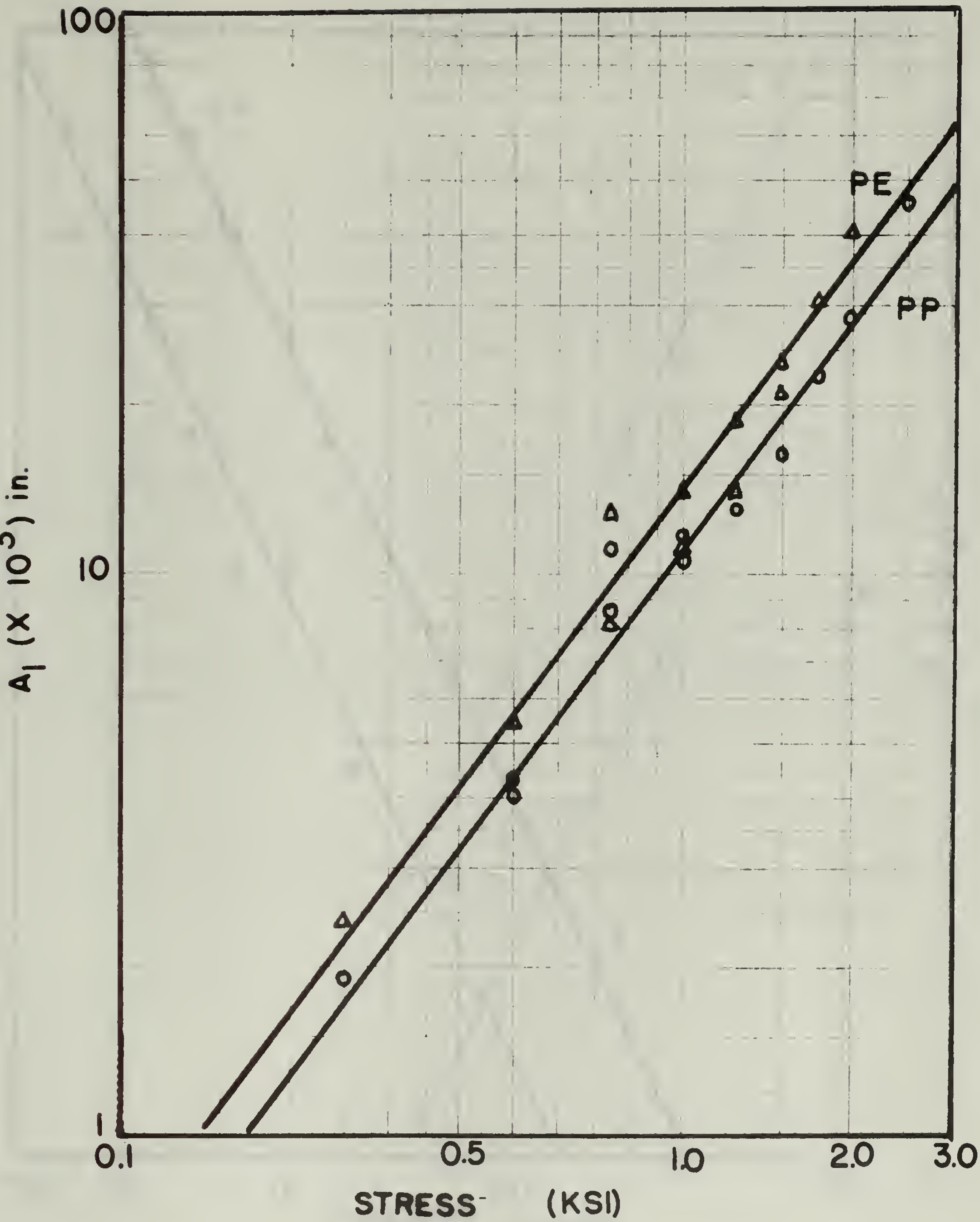


FIGURE 26 Log A_1 vs. Log STRESS, SINGLE COMPONENTS

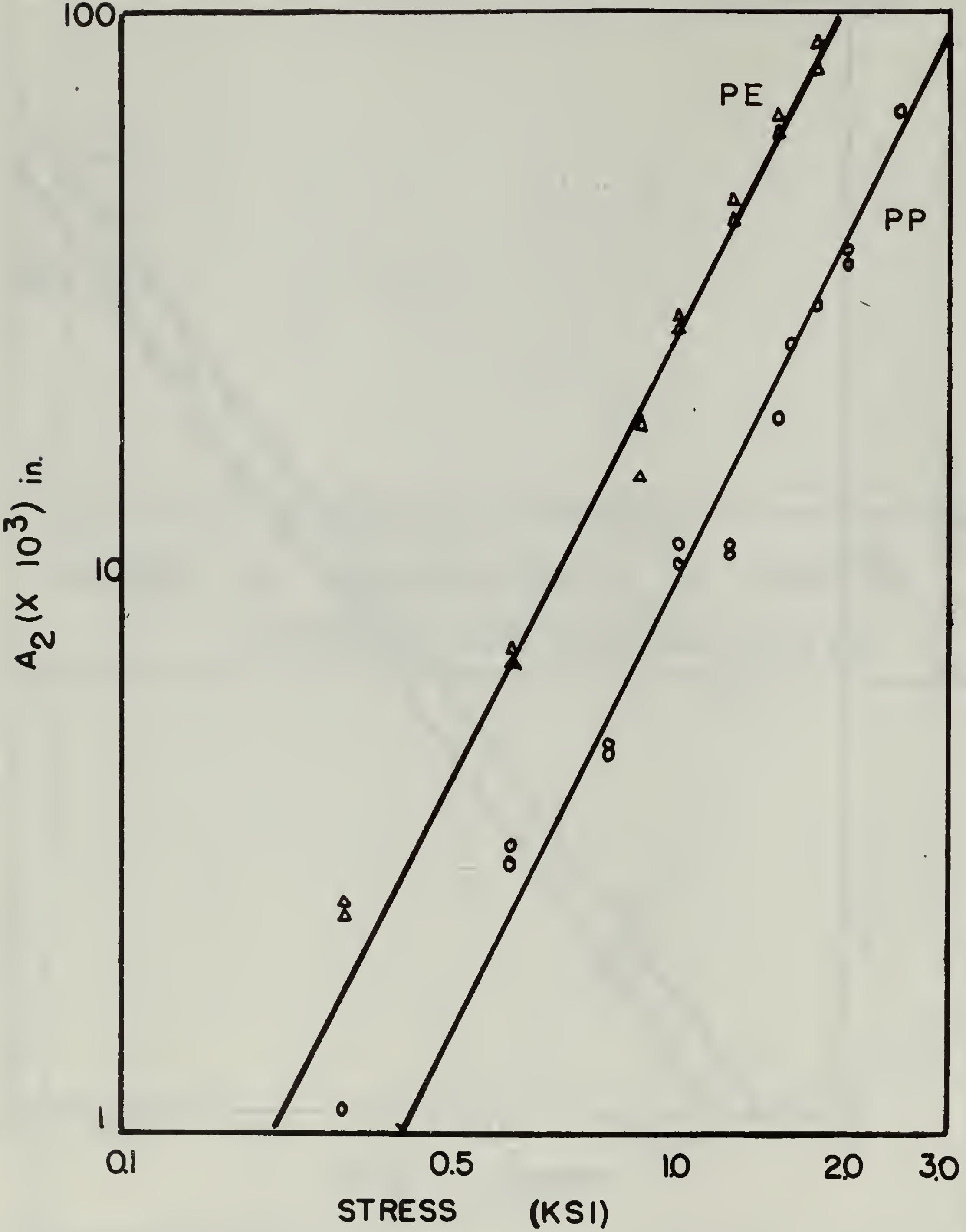


FIGURE 27 Log A_2 vs. Log STRESS, SINGLE COMPONENTS

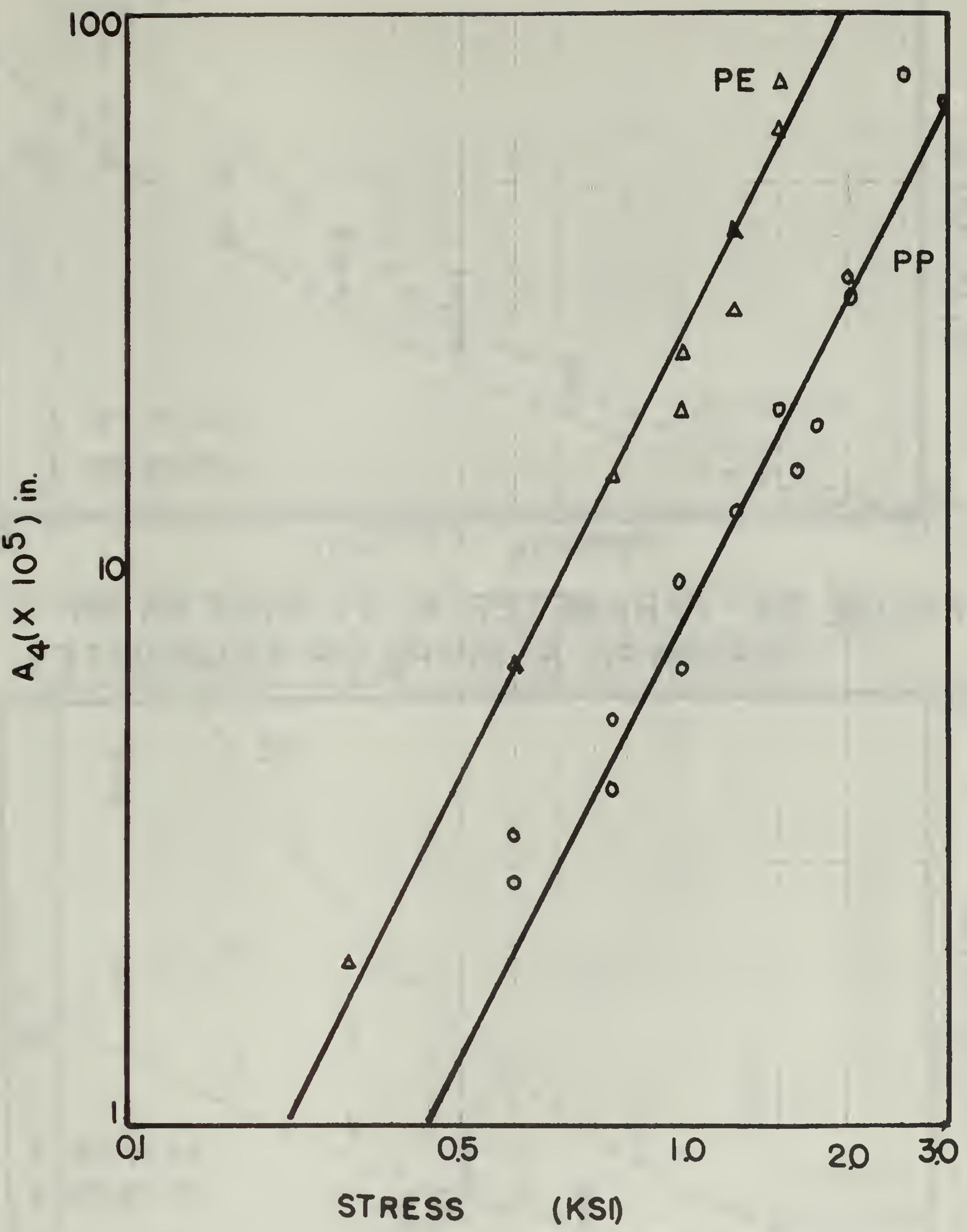


FIGURE 28 Log A_4 vs. Log STRESS, SINGLE COMPONENTS

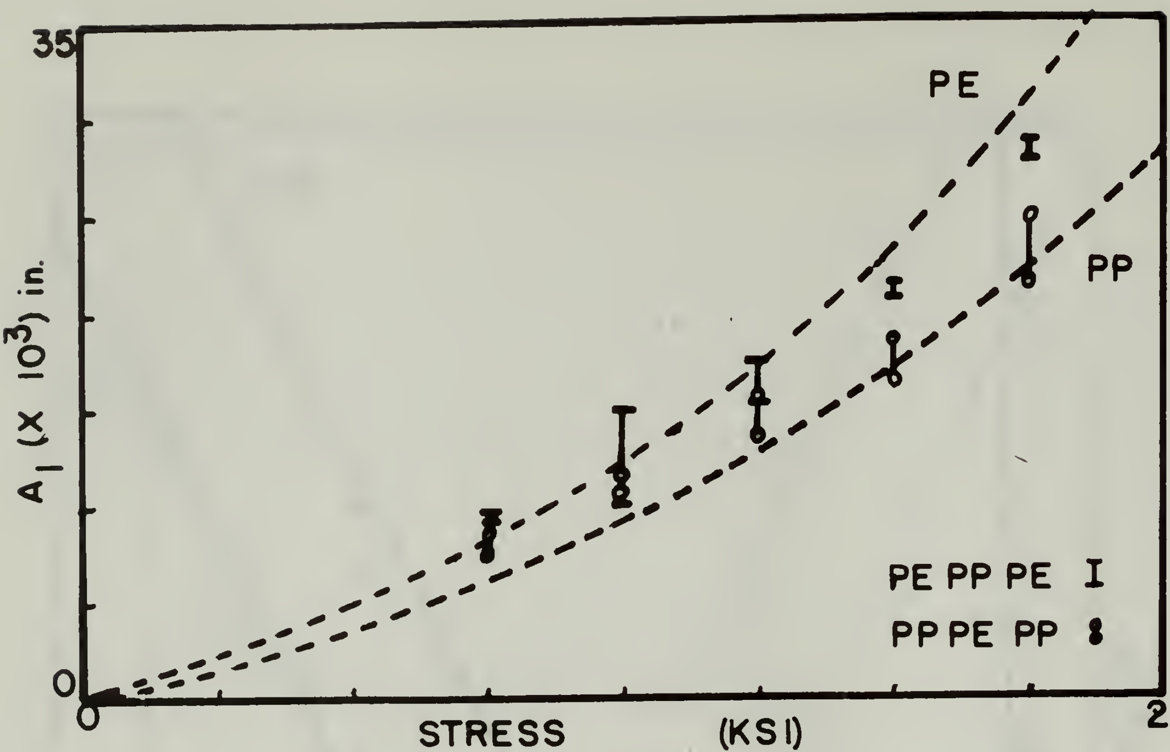


FIGURE 29 PARAMETER A_1 vs. STRESS for PE/PP/PE & PP/PE/PP COMPOSITES

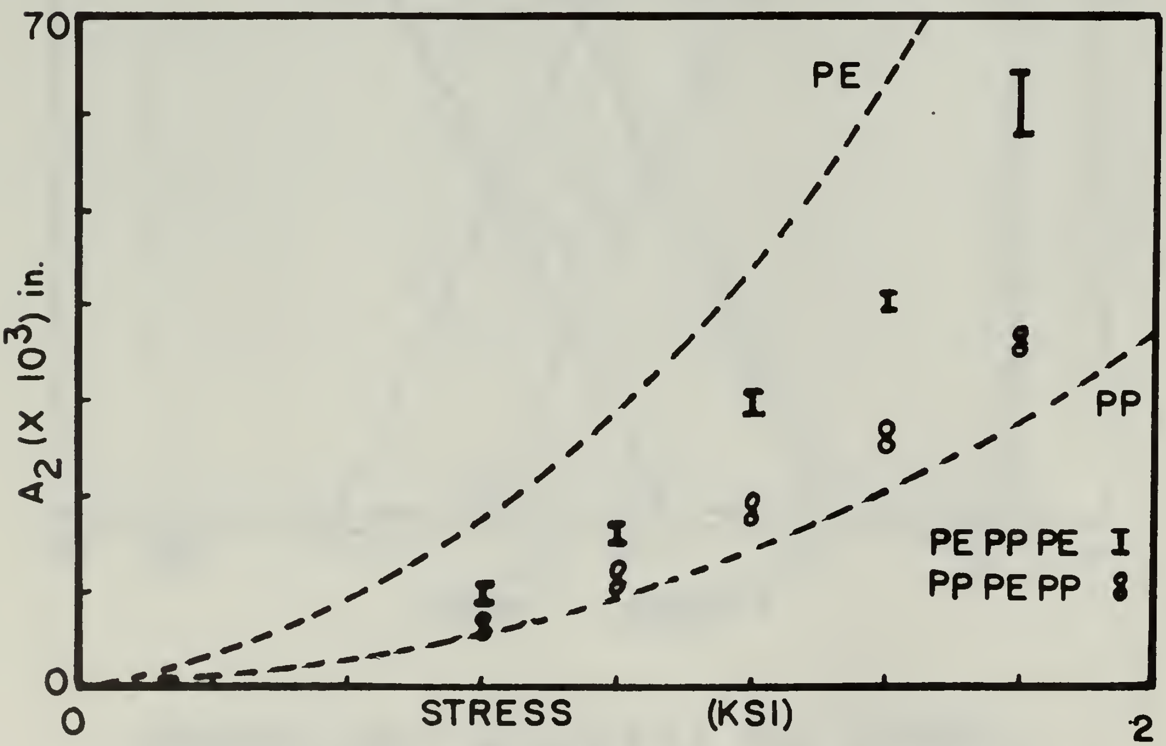


FIGURE 30 PARAMETER A_2 vs. STRESS for PE/PP/PE & PP/PE/PP COMPOSITES

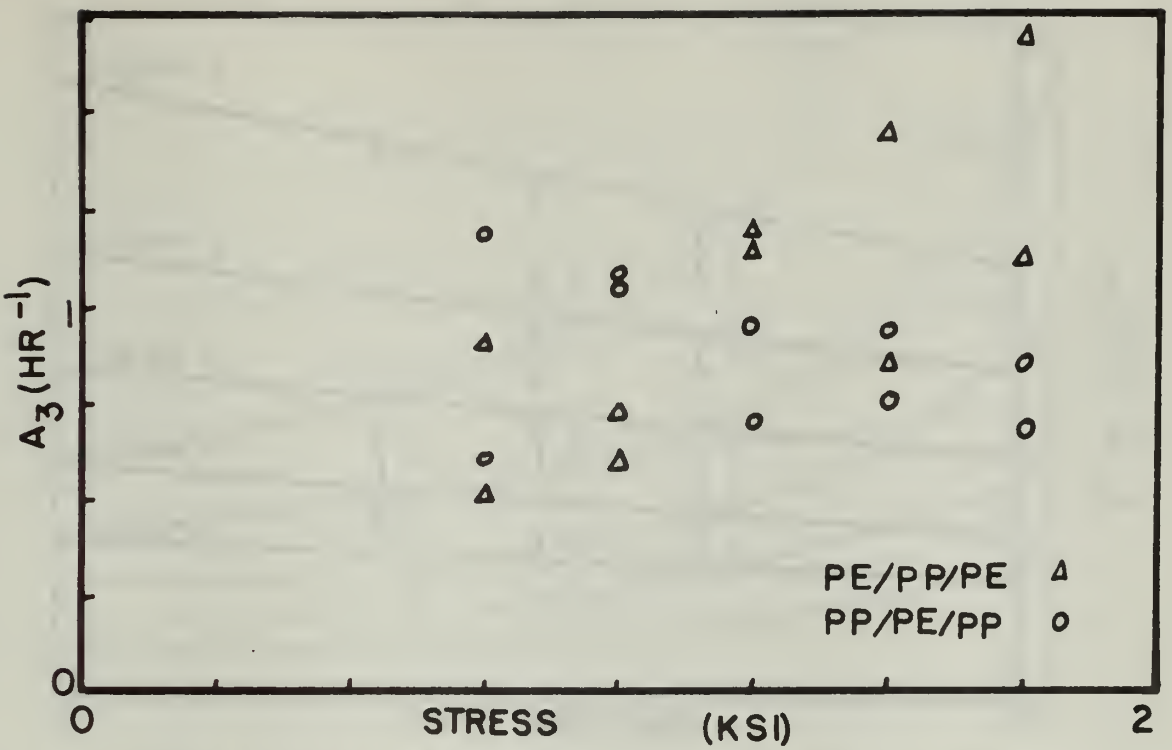


FIGURE 31 PARAMETER A_3 vs. STRESS for PE/PP/PE & PP/PE/PP COMPOSITES

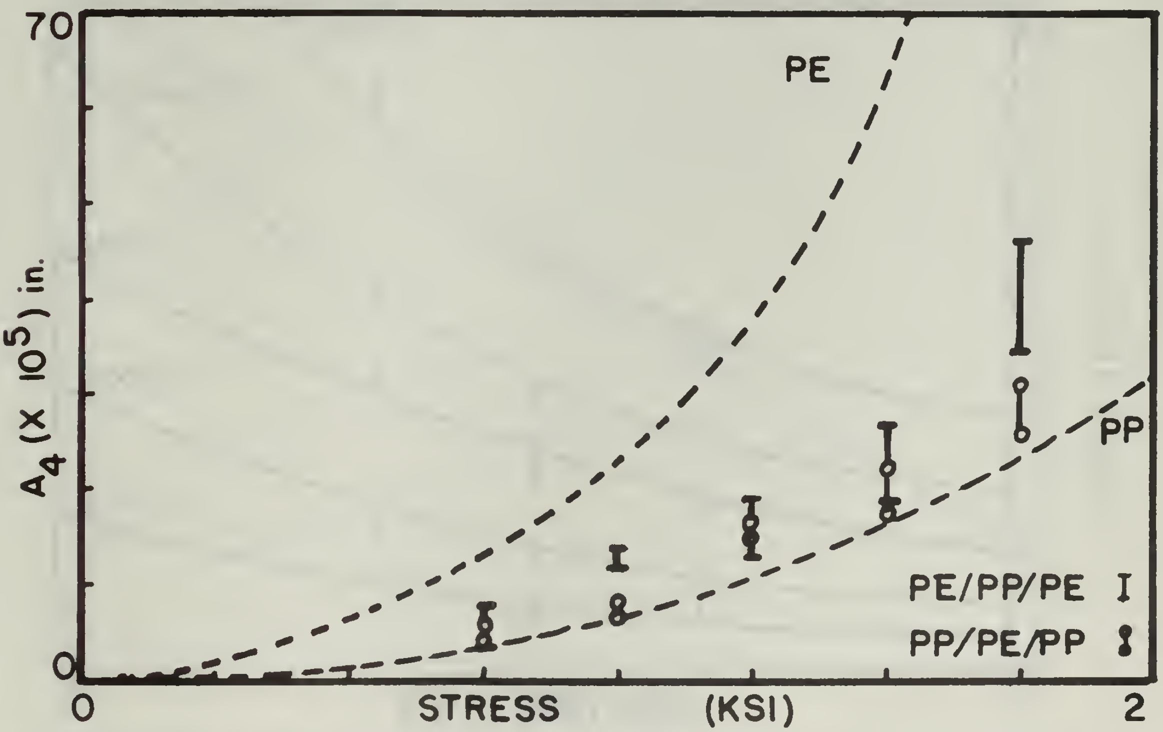


FIGURE 32 PARAMETER A_4 vs. STRESS for PE/PP/PE & PP/PE/PP COMPOSITES

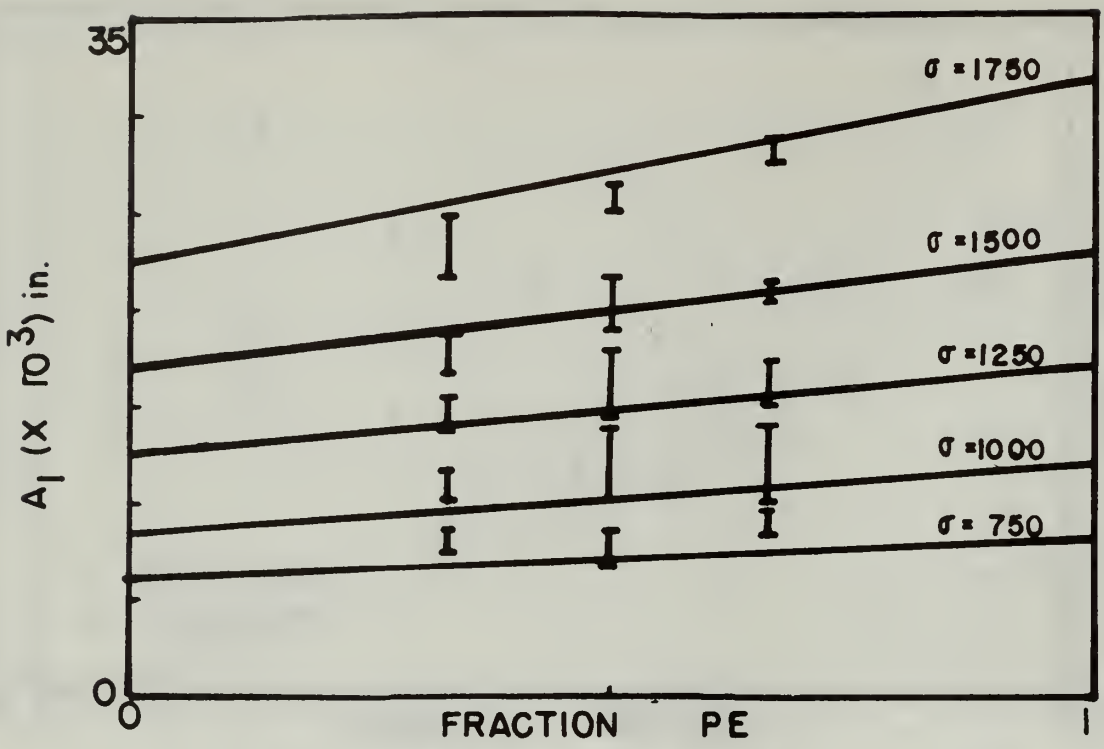


FIGURE 33 PARAMETER A_1 vs. VOLUME FRACTION PE in PE/PP COMPOSITES

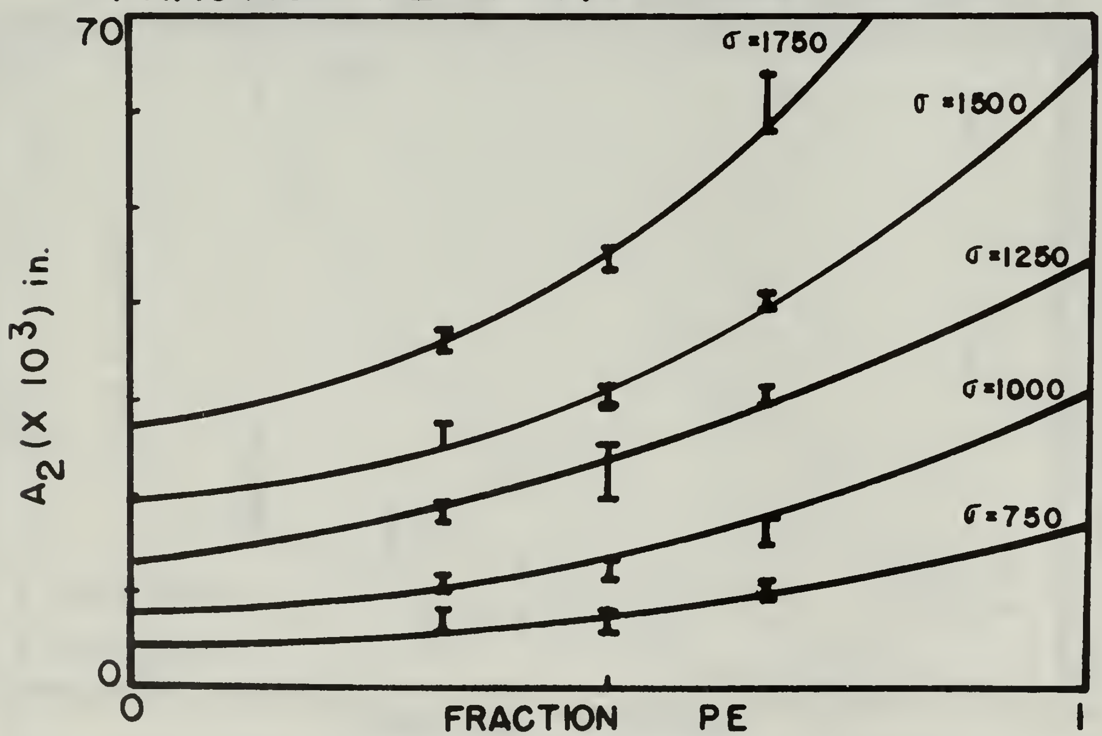


FIGURE 34 PARAMETER A_2 vs. VOLUME FRACTION PE in PE/PP COMPOSITES

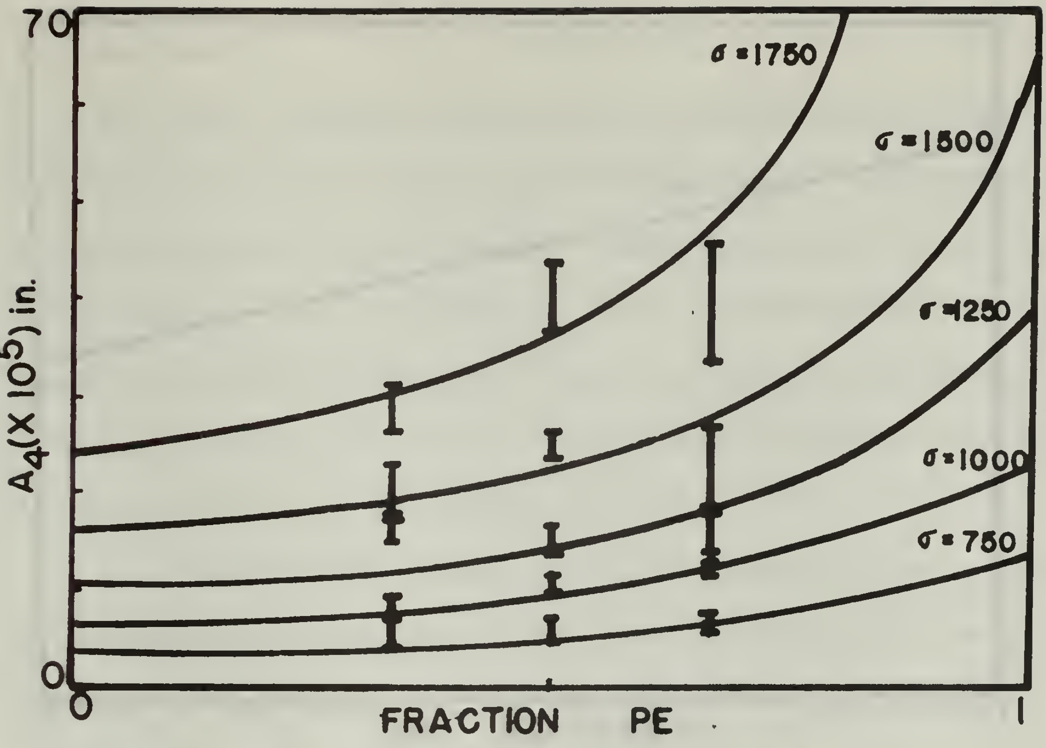


FIGURE 35 PARAMETER A_4 vs. VOLUME FRACTION PE in PE/PP COMPOSITES

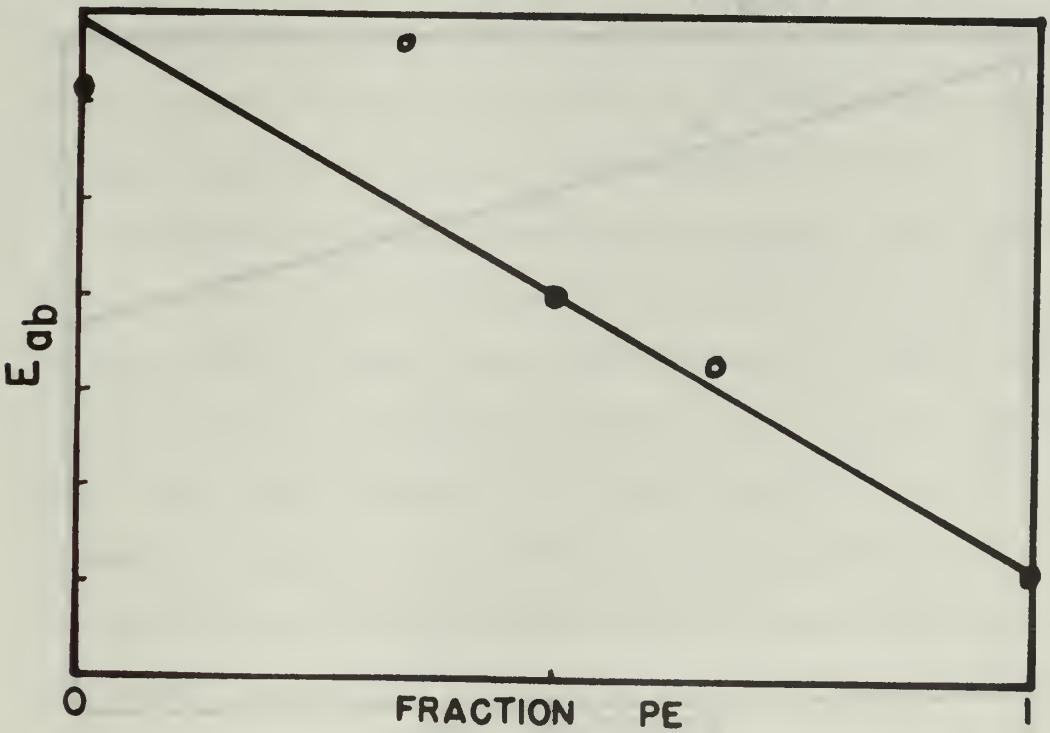


FIGURE 36 E_{ab} vs. VOLUME FRACTION PE in PE/PP COMPOSITES

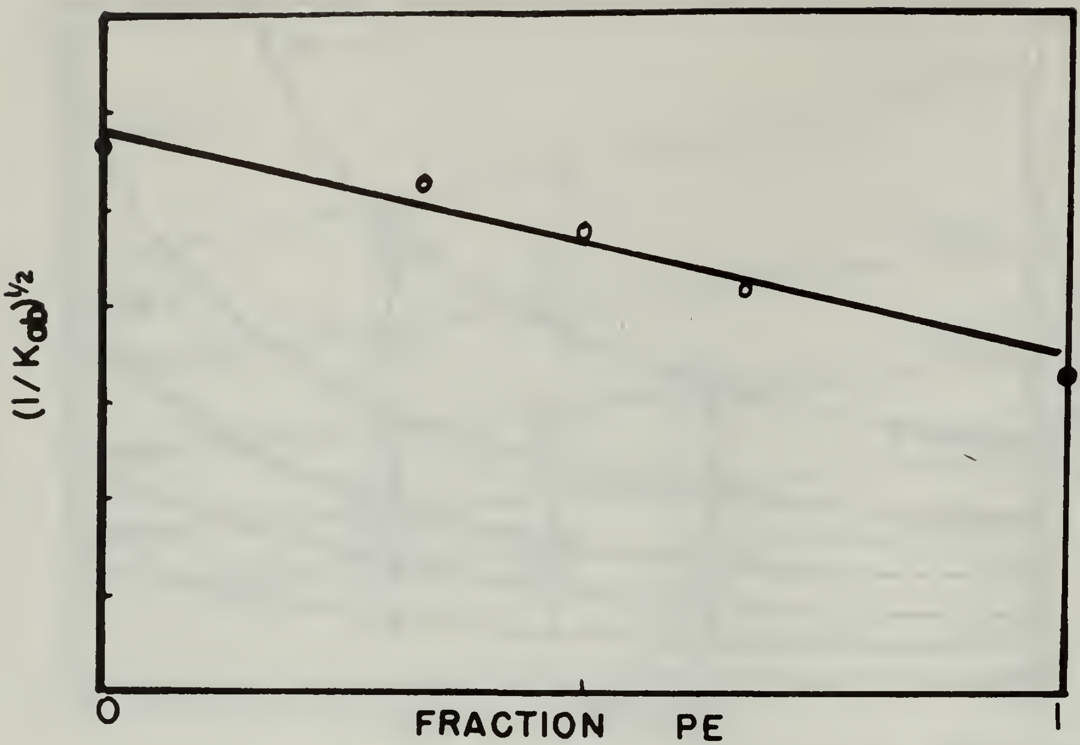


FIGURE 37 $\left(\frac{1}{K_{ab}}\right)^{1/2}$ vs VOLUME FRACTION PE

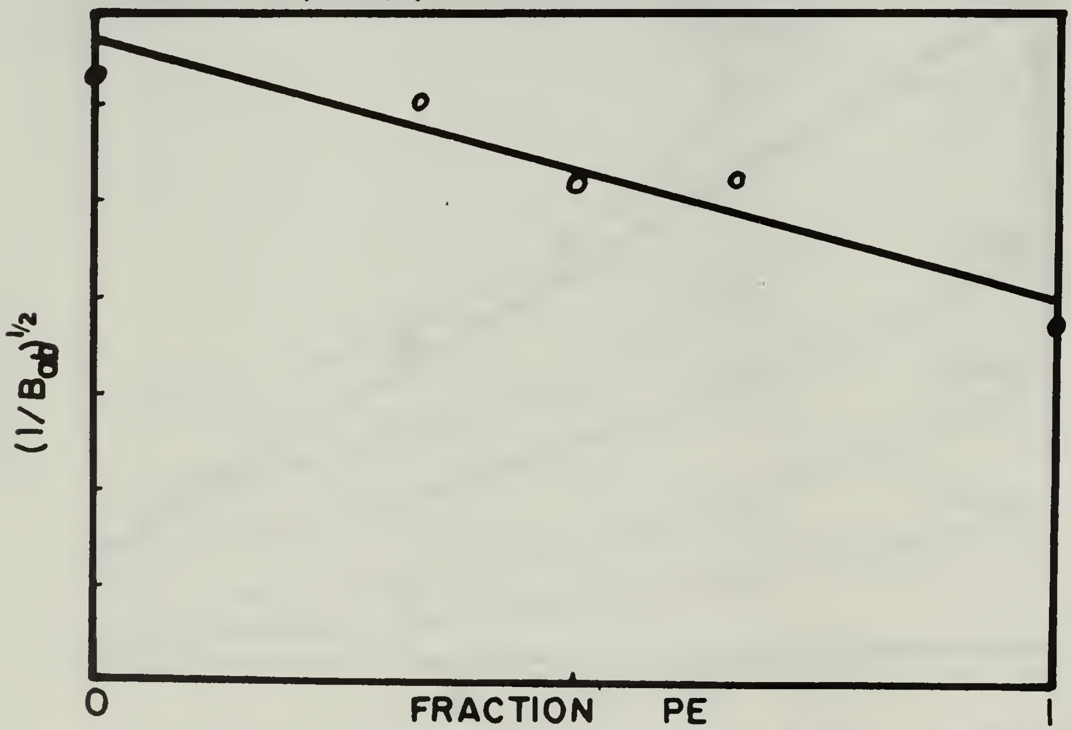


FIGURE 38 $\left(\frac{1}{B_{ab}}\right)^{1/2}$ vs. VOLUME FRACTION PE

7. Conclusions.

The simple laminated composites of polyethylene and polypropylene were prepared and the creep behavior was measured. The parametric characteristics were determined by least squaring the data. These characteristics were compared with those predicted by theoretical analysis and were found to agree quite closely with the predicted results, ie., the creep behavior was a linear function of the properties of each component and its relative volume.

This investigation provides conclusive evidence that a combined mathematical and experimental approach in determining the relative creep behavior of composites is a powerful tool. The basic analysis of the behavior of simple composites is a useful method of predicting creep behavior in the more sophisticated composite systems in addition to the conventional methods for ad hoc measurements. It is necessary, however, that a computer facility be available to the experimenter and that an empirical equation can be used to represent this behavior.

The measurements which were obtained required total elapsed times which were too short for engineering purposes, but any further decrease in creep rate for longer times would have been due largely to the crystallization or strengthening effect as the material elongated under load. This effect was ignored as a first approximation even though it becomes quite apparent in the data. It is to be noted, however, that some polyethylene specimens broke outside the gauge length after one and one-half months under moderate stress. This failure appeared brittle in nature and occurred at the hole in the specimen. These failures would have prevented taking data for times greater than 1000 hours.

The following recommendations are submitted for further work:

(1) A higher order empirical equation be tested whereby two relaxation time constants can be determined and an allowance for the crystallization or structure factor can be made.

(2) Stress relaxation data be correlated with simple tension creep data to determine the interrelation through the relaxation mechanisms of the composites.

(3) Other materials be tested which can be fabricated into true composites of known composition without the difficulties of structural change and poor adhesive properties.

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APPENDIX A

TABULATED DATA BY GROUPS

SINGLE POLYETHYLENE SPECIMENS

RUN	STRESS (PSI)	% PP	% PE	A_1 (X 10^3) (IN.)	A_2 (X 10^3 (IN.)	A_3 (HR.$^{-1}$)	A_4 (X 10^5) (IN./HR.)
1	244.4	0.0	100.0	2.39	2.68	0.62	1.93
2	497.5			5.49	7.39	3.78	5.92
3	742.1			12.91	19.29	2.00	4.86
4	754.0			8.15	15.40	1.59	14.80
5	998.9			14.03	28.80	1.24	19.52
6	1001.6			11.27	27.41	1.28	24.77
7	1244.7			13.78	46.49	1.39	42.67
8	1248.9			18.53	43.01	1.04	28.86
9	1494.5			20.89	63.19	1.65	75.12
10	1502.3			24.22	66.18	1.37	61.55
11	1744.2			30.71	78.34	1.55	294.79
12	1752.9			32.54	88.36	0.97	301.00
13	1995.1			40.92	133.60	0.79	225.84

SINGLE POLYPROPYLENE SPECIMENS

RUN	STRESS (PSI)	% PP	% PE	A_1 (X 10^3) (IN.)	A_2 (X 10^3) (IN.)	A_3 (HR.$^{-1}$)	A_4 (X 10^5) (IN./HR.)
1	251.4	100.0	0.0	1.91	1.10	0.73	2.20
2	504.3			4.11	3.04	0.69	2.71
3	504.1			4.37	3.33	0.50	3.36
4	613.1			5.52	3.04	3.52	9.96
5	749.1			11.28	4.81	0.45	4.03
6	752.9			8.55	4.88	0.57	5.28
7	999.6			11.71	10.45	0.46	9.45
8	1001.0			10.82	11.77	0.52	6.69
9	1251.6			12.90	11.08	0.89	12.89
10	1501.4			16.35	19.02	1.06	19.47
11	1603.4			19.81	26.36	0.60	14.82
12	1753.6			22.91	30.70	0.98	18.39
13	2003.8			29.08	37.75	0.88	31.44
14	1997.2			28.78	35.97	1.01	33.96
15	2502.3			45.74	68.33	0.58	77.82

POLYETHYLENE/POLYPROPYLENE COMPOSITES WITHOUT AUXILIARY CLAMPS

RUN	STRESS (PSI)	% PP	% PE	A_1 (X 10^3) (IN.)	A_2 (X 10^3) (IN.)	A_3 (HR.$^{-1}$)	A_4 (X 10^5) (IN./HR.)
1	500.4	50.7	49.3	5.55	3.62	2.78	3.53
2	501.2	50.9	49.1	8.08	3.83	0.48	2.11
3	748.7	50.9	49.1	8.70	6.45	0.66	5.86
4	752.0	51.4	48.6	7.20	8.56	0.95	7.20
5	999.2	52.1	47.9	10.13	14.60	0.88	11.21
6	1000.0	51.1	48.9	14.14	13.93	1.01	11.58
7	1252.4	50.7	49.3	18.07	21.06	0.97	14.31
8	1252.9	51.3	48.7	13.97	25.19	0.90	17.44
9	1500.0	51.5	48.5	21.57	30.92	1.01	26.20
10	1481.7	51.1	48.9	19.16	29.99	1.15	24.16
11	1747.6	51.6	48.4	26.33	44.52	1.08	44.25
12	1753.1	51.0	49.0	26.97	44.10	0.94	37.54

POLYETHYLENE/POLYPROPYLENE COMPOSITES WITH ONE AUXILIARY CLAMP

RUN	STRESS (PSI)	% PP	% PE	A_1 (X 10^3) (IN.)	A_2 (X 10^3) (IN.)	A_3 (HR.$^{-1}$)	A_4 (X 10^5) (IN./HR.)
1	499.5	50.5	49.5	9.03	3.22	0.48	2.29
2	1001.6	51.6	48.4	12.22	17.18	0.47	8.15
3	999.3	50.5	49.5	12.43	15.84	0.60	8.38
4	999.1	50.5	49.5	11.52	15.79	0.47	8.99
5	999.1	50.5	49.5	12.41	15.52	0.73	11.37
6	999.7	50.5	49.5	11.62	16.20	0.57	8.16
7	1249.5	51.3	49.7	20.33	26.37	0.75	12.34
8	1247.3	50.7	49.3	17.95	24.37	0.90	18.04
9	1499.8	50.4	49.6	23.06	36.18	0.80	17.87
10	1501.5	51.4	48.6	22.06	31.48	0.94	24.24
11	1496.8	50.5	49.5	18.74	32.19	0.78	23.85
12	1495.8	52.4	47.6	15.22	29.79	1.44	27.82
13	1750.5	50.7	49.3	28.27	52.50	0.77	27.17
14	1752.4	50.6	49.4	27.05	46.26	0.82	37.64

POLYETHYLENE/POLYPROPYLENE COMPOSITES WITH TWO AUXILIARY CLAMPS

RUN	STRESS (PSI)	% PP	% PE	A_1 (X 10^3) (IN.)	A_2 (X 10^3) (IN.)	A_3 (HR.$^{-1}$)	A_4 (X 10^5) (IN./HR.)
1	999.3	51.0	49.0	12.45	14.25	0.71	12.40
2	999.3	50.8	49.2	14.32	16.91	0.98	12.95
3	1001.0	50.7	49.3	11.25	17.30	0.46	8.65
4	1501.5	53.2	46.8	19.37	29.46	0.98	21.65
5	1496.8	51.2	48.8	18.37	35.43	0.87	26.28

POLYETHYLENE/POLYPROPYLENE COMPOSITES WITH THREE AUXILIARY CLAMPS							
RUN	STRESS (PSI)	% PP	% PE	A_1 (X 10^3) (IN.)	A_2 (X 10^3) (IN.)	A_3 (HR.$^{-1}$)	A_4 (X 10^5) (IN./HR.)
1	989.2	50.9	49.1	14.55	16.27	0.41	8.00
2	1000.2	50.9	49.1	11.07	15.91	0.78	12.61
3	1503.0	54.1	45.9	22.82	31.93	0.96	23.83
4	1502.7	50.7	49.3	19.34	35.10	0.94	26.10
5	1494.7	52.7	47.3	17.96	30.92	0.78	20.23

POLYETHYLENE/POLYPROPYLENE COMPOSITES WITH FOUR AUXILIARY CLAMPS							
RUN	STRESS (PSI)	% PP	% PE	A_1 (X 10^3) (IN.)	A_2 (X 10^3) (IN.)	A_3 (HR.$^{-1}$)	A_4 (X 10^5) (IN./HR.)
1	992.2	51.0	49.0	10.94	18.71	0.39	8.43
2	999.3	50.7	49.3	12.90	14.08	0.77	11.60
3	1494.7	52.7	47.3	17.97	30.92	0.78	20.23
4	1502.0	51.8	48.2	19.21	32.87	0.91	23.19

PE/PP/PE COMPOSITES WITHOUT AUXILIARY CLAMPS							
RUN	STRESS (PSI)	% PP	% PE	A_1 (X 10^3) (IN.)	A_2 (X 10^3) (IN.)	A_3 (HR.$^{-1}$)	A_4 (X 10^5) (IN./HR.)
1	749.6	34.1	65.9	8.27	8.68	1.19	8.04
2	750.0	34.0	66.0	8.85	10.75	0.61	6.09
3	1001.0	34.0	66.0	14.81	17.94	1.09	11.87
4	1000.6	33.9	66.1	9.66	15.90	1.06	13.76
5	1250.5	34.0	66.0	15.33	31.85	0.70	12.93
6	1247.2	33.8	66.2	17.64	28.38	0.97	19.25
7	1503.7	33.6	66.4	21.87	39.34	0.93	27.18
8	1500.4	33.9	66.1	22.64	42.29	0.76	18.85
9	1751.1	33.9	66.1	28.37	57.21	0.85	46.28
10	1747.7	33.9	66.1	27.33	64.58	0.67	33.56

PP/PE/PP COMPOSITES WITHOUT AUXILIARY CLAMPS							
RUN	STRESS (PSI)	% PP	% PE	A_1 (X 10^3) (IN.)	A_2 (X 10^3) (IN.)	A_3 (HR.$^{-1}$)	A_4 (X 10^5) (IN./HR.)
1	751.5	67.2	32.8	8.75	5.95	0.90	5.72
2	755.2	67.3	32.7	7.54	7.40	0.52	4.33
3	1000.7	67.4	32.6	11.64	10.65	0.74	7.63
4	1001.5	67.8	32.2	10.72	12.49	0.60	6.35
5	1246.2	67.3	32.7	13.62	17.52	1.14	16.40
6	1250.8	67.3	32.7	16.14	19.23	1.20	14.84
7	1491.5	66.8	33.2	16.50	25.29	1.45	22.56
8	1502.7	67.7	32.3	18.38	26.59	0.85	17.81
9	1748.3	67.5	32.5	24.88	36.60	1.13	25.65
10	1753.3	67.0	33.0	21.58	35.51	1.70	33.17

SINGLE POLYETHYLENE SPECIMENS (TRANSVERSE ORIENTATION)							
RUN	STRESS (PSI)	% PP	% PE	A_1 (X 10^3) (IN.)	A_2 (X 10^3) (IN.)	A_3 (HR.$^{-1}$)	A_4 (X 10^5) (IN./HR.)
1	254.3	0.0	100.0	2.19	2.35	1.48	2.18
2	497.5			5.13	6.57	1.45	5.07
3	748.7			9.20	14.19	1.45	10.07
4	998.2			12.16	22.64	1.08	14.31
5	1251.1			16.83	36.45	1.00	21.18

APPENDIX B

FORTRAN 60 COMPUTER PROGRAMS USED IN ANALYSIS

Two basic Fortran 60 computer programs were used in calculating the parameters A_1 through A_4 and comparing the data with the least squares fitted equation:

$$\Delta L = A_1 + A_2(1 - \exp(- A_3 t)) + A_4 t.$$

The first program called PROGRAM CREEP is a modification of a basic Least Squares program developed by Dr. W. Tolles of the Materials Science and Chemistry Department of the Naval Postgraduate School. The program is annotated by comment cards and needs no further explanation. The second program called PROGRAM CREEPDRW is a drawing program used to check the fitted equation with the data used. The off-line plotting subroutine J7-NPS-DRAW programmed by J. R. Ward of NPGS was available in the CDC 1604 Digital Computer System. Test data is included with each program for reference only and should not be used as actual data.

```
..JOB0630,HOWARD MA
      PROGRAM CREEP
C  WRITE FUNCTION SUBPROGRAM TO CALCULATE THE FUNCTION TO BE LEAST SQUARED.
C  A IS DIMENSIONED 10 AND CONTAINS THE PARAMETERS TO BE VARIED SUCH AS TO
C  MINIMIZE THE SUM OF ERRORS SQUARED X, XB, AND XC ARE THE THREE INDEPENDENT
C  PARAMETERS (YOU MAY WISH TO USE ONLY X) NOF IS THE FUNCTION NUMBER - USED FOR
C  BRANCHING TO DIFFERENT PARTS OF THE EQN SUBPROGRAM WHEN SEVERAL FUNCTIONS
C  ARE TO BE FIT (FOR SEVERAL JOBS TO BE DONE).
C  THE DIMENSIONED ARRAYS HAVE THE FOLLOWING MEANING--
C     A(1 ) CONTAINS THE PARAMETERS WHICH ARE TO BE VARIED.
C  X(200), XB(200), AND XC(200) CONTAIN THE INDEPENDENT VARIABLES.
C  Z(200) CONTAINS THE OBSERVED VALUES OF THE FUNCTION (THE OBSERVED DEPENDENT
C  PARAMETERS).
C  FINCR(10) CONTAINS THE MAGNITUDE OF THE INCREMENTS FOR THE PARAMETERS A(10)
C  SO THAT THE PROGRAM MAY TAKE NUMERICAL DERIVATIVES WITH REASONABLE ACCURACY.
C  R(200) CONTAINS THE DIFFERENCE BETWEEN OBSERVED (Z(200)) AND CALCULATED
C  E(10) CONTAINS THE ESTIMATES OF THE ERRORS OF THE PARAMETERS A(10) AFTER
C  ITERATION.
C     INPUT
C  FIRST CARD - WILL BE REPRODUCED ON OUTPUT USED FOR LABELING.
C  SECOND CARD FORMAT(I2,I3,I2,I3,1E10.2,55X,I5)
C  IR= NUMBER OF PARAMETERS TO BE VARIED
C  IS= NUMBER OF POINTS
C  NOF = FUNCTION NUMBER (SEE ABOVE)
C  NINP = NUMBER OF INDEPENDENT PARAMETERS
C  EPSIL = IS USED AS A CRITERION FOR CONVERGENCE. IF THE RELATIVE VALUE
C  OF THE RESIDUAL CHANGES BY LESS THAN EPSIN IN TWO SUCCESSIVE ITERATIONS,
C  CONVERGENCE IS REACHED.
C  IO = SIGNAL FLAG WHEN NOT ZERO CAUSES COEFFICIENT MATRIX TO BE PRINTED.
C  THIRD CARD FORMAT(A6,1F9.0,3F10.0)
C  RUN = IDENTIFICATION CODE (6 ALPHANUMERIC FIGURES)
C  WT = LOAD WEIGHT APPLIED TO LEVER ARM OF MACHINE.
C  APP = FRACTIONAL AREA OF SPECIMEN WHICH IS POLYPROPYLENE.
C  APE = SAME AS APP EXCEPT APPLIES TO POLYETHYLENE.
C  ARM = MACHINE LEVER ARM RATIO.
C  FOURTH CARD(S) - FORMAT (5E14.6) - CONTAIN YOUR ESTIMATE OF THE PARAMETERS,
```

```
C  A(10)
C  FIFTH CARD(S) - FORMAT (5E14.6) - CONTAIN THE INCREMENTS FOR THE A(10) FOR
C  OBTAINING NUMERICAL DERIVATIVE.
C  SIXTH CARD(S) - FORMAT (14F5.1) - CONTAIN Z(I), OR THE OBSERVED,
C  DEPENDENT VARIABLES.
C  SEVENTH CARD(S) - FORMAT (7F10.5) - CONTAIN X(I), OR THE VALUES OF THE
C  FIRST INDEPENDENT VARIABLE.
C  EIGTH CARD(S) AND NINTH CARD(S) ARE READ IN ONLY IF NINP IS GREATER THAN
C  UNITY, AND CONTAIN XB(I) AND XC(I), THE SECOND AND THIRD INDEPENDENT
C  VARIABLES.  NOTE THE ABSENCE OF INPUT/OUTPUT STATEMENTS IN THIS PROGRAM.
C  STACKING OF JOBS IS PERMITTED - THE PROGRAM STOPS WHEN IT READS A ZERO FOR IR
C  (SECOND CARD INPUT), THUS SEVERAL BLANK CARDS AFTER LAST JOB IS
C  SUFFICIENT TO STOP ROUTINE.
      DIMENSION A(10), X(200), XB(200), XC(200), Z(200), FINCR(10),
     1R(200), E(10)
    1 READ 106
      READ 100, IR,IS,NOF,NINP,EPSIL,IO
      IF(IR)200,200,9
    9 READ 99, RUN,WT,APP,APE,ARM
   10 READ 101, (A(I), I = 1,IR)
      READ 101, (FINCR(I), I = 1,IR)
      READ 102,(Z(I),I=1,IS)
      READ 103, (X(I), I = 1,IS)
      DO 11 I=1,IS
   11 Z(I)=Z(I)/1000.
   18 AREA=APP+APE
      PCTPP=APP/AREA
      PCTPE=APE/AREA
      STRESS=WT*ARM/AREA
      PRINT 105
   20 PRINT 106
      PRINT 109
      PRINT 107
      PRINT 108, (IR,IS,NOF,NINP,EPSIL)
      PRINT 109
      PRINT 96
```

```
      PRINT 109
      PRINT 97,RUN,STRESS,PCTPP,PCTPE
      PRINT 109
      PRINT 110
      PRINT 109
      PRINT 111, (A(I), I = 1,IR)
      PRINT 109
      PRINT 112
      PRINT 109
      PRINT 111, (FINCR(I), I = 1,IR)
      PRINT 109
      PRINT 113
      PRINT 109
      PRINT 114, (Z(I), I = 1,IS)
      PRINT 109
      PRINT 115
      PRINT 109
      PRINT 116, (X(I), I = 1,IS)
      PRINT 109
   30 CALL LEAST(IR,IS,A,X,XB,XC,Z,FINCR,EPSIL,NOITR,RRQ,NOF,R,E,IO)
      PRINT 109
      PRINT 119
      PRINT 109
      PRINT 120, (A(I), I = 1,IR)
      PRINT 109
      PRINT 124
      PRINT 109
      PRINT 120, (E(I), I = 1,IR)
      PRINT 109
      PRINT 121, NOITR, RRQ
      PRINT 109
      PRINT 122
      PRINT 109
      PRINT 123, (R(I), I = 1,IS)
      GO TO 1
   96 FORMAT (45H     RUN     STRESS          PCTPP        PCTPE)
```

```
 97 FORMAT (4X,A6,F11.2,2F12.4)
 99 FORMAT (A6,1F9.0,3F10.0)
100 FORMAT (I2,I3,I2,I3,1E10.2,55X,I5)
101 FORMAT (5E14.6)
102 FORMAT (14F5.1)
103 FORMAT (7F10.5)
105 FORMAT (1H1)
106 FORMAT (80H
   1                              )
107 FORMAT (98H NUMBER OF PARAMETERS     NUMBER OF POINTS     FUNCTION
   1 NUMBER    NUMBER OF INDEP VAR      EPSILON)
108 FORMAT (8X,I2,24X,I3,17X,I2,19X,I2,12X,E10.2)
109 FORMAT (1H )
110 FORMAT (26H THE PARAMETERS FED IN ARE)
111 FORMAT (1H ,5E14.6)
112 FORMAT (55H THE INCREMENTS FOR OBTAINING NUMERICAL DERIVATIVES ARE
   1)
113 FORMAT (34H THE OBSERVED VALUES TO BE FIT ARE)
114 FORMAT (5E14.6)
115 FORMAT (30H THE INDEPENDENT VARIABLES ARE)
116 FORMAT (1H ,5E14.6)
119 FORMAT (38H THE BEST VALUES OF THE PARAMETERS ARE)
120 FORMAT (1H ,7E17.10)
121 FORMAT (24H NUMBER OF ITERATIONS = ,I2,50H    THE SUM OF THE SQUAR
   1ES OF THE ERRORS IS NOW = ,E12.6)
122 FORMAT (53H OBSERVED MINUS CALCULATED VALUES OF THE BEST FIT ARE)
123 FORMAT (1H ,9E12.5)
124 FORMAT (66H ESTIMATES OF THE ERROR IN EACH PARAMETER ARE (STANDARD
   1 DEVIATION))
200 STOP
    END
C
    SUBROUTINE LEAST(IR,IS,A,X,XB,XC,Z,FINCR,EPSIL,NOITR,RRQ,NOF,R,E,
   1IO)
C  IR = NO. OF PARAMETERS, IS = NO. OF POINTS, A IS ARRAY OF PARAMETERS,
C  X IS INDEPENDENT VARIABLE, Z DEPENDENT.  FINCR IS ARRAY OF INCREMENTS OF
```

```
C  PARAMETERS.  EPSIL IS -FRACTIONAL- ERROR CRITERION.  NOITR IS NO. OF
C  ITERATIONS REQUIRED (UP TO 10).  RRQ = SUM OF SQUARES OF RESIDUALS.
C  NOF IS NUMBER OF THE FUNCTION USEN IN  EQN-.
C  E IS THE ARRAY OF ESTIMATED ERRORS IN THE PARAMETERS.
      DIMENSION A(10), X(200), XB(200), XC(200), Z(200), FINCR(10), R(20
     10), D(200,10), DT(10,200), DEL(10), DS(10), DPI(10,10), DP(10,10),
     2E(1 )
      NOITR = 0
      DO 20 I = 1,IS
   20 R(I) = Z(I) - EQN(A,X(I),XB(I),XC(I),NOF)
   25 IF (NOITR-9) 130,130,104
  130 NOITR = NOITR + 1
      DO 220 J = 1, IR
      A(J) = A(J)+FINCR(J)
      DO 15 I = 1,IS
   15 D(I,J) = EQN(A,X(I),XB(I),XC(I),NOF)
      A(J) = A(J)-FINCR(J)
  220 CONTINUE
      DO 30 I = 1,IS
      CONST = EQN(A,X(I),XB(I),XC(I),NOF)
      DO 30 J = 1,IR
   30 D(I,J) = (D(I,J)-CONST)/FINCR(J)
      IF (IO) 31,33,31
   31 DO 32 I=1,IR
   32 PRINT 102, (D(J,I), J=1,IS)
  102 FORMAT (1H ,11F10.3)
   33 CONTINUE
      DO 35 I = 1,IS
      DO 35 J = 1,IR
   35 DT(J,I) = D(I,J)
      DO 36 I = 1,IR
      DO 36 J = 1,IR
      DP(I,J) = 0.0
      DO 36 K = 1,IS
   36 DP(I,J) = DP(I,J)+DT(I,K)*D(K,J)
       CALL GAUSS3 (IR,1.00E-30,DP,DPI,KER)
```

```
      IF(KER-1) 120,37,120
   37 DO 40 I = 1,IS
      DO 38 J = 1,IR
      DS(J) = 0.0
      DO 38 K = 1,IR
   38 DS(J) = DS(J)+DPI(J,K)*DT(K,I)
      DO 39 L = 1,IR
   39 DT(L,I) = DS(L)
   40 CONTINUE
      DO 110 I = 1, IR
      DEL(I) = 0.0
      DO 110 J = 1, IS
  110 DEL(I) = DEL(I)+DT(I,J)*R(J)
      DO 10 I = 1,IR
   10 A(I) = A(I)+DEL(I)
      DO320 I = 1,IS
  320 R(I) = Z(I) - EQN(A,X(I),XB(I),XC(I),NOF)
      RRQ = 0.0
      DO 50 I = 1,IS
   50 RRQ = RRQ+R(I)**2
      CRES = ABSF(RRQ-RRP) - EPSIL*RRP
      RRP = RRQ
      IF(CRES) 100,100,25
  104 PRINT 101
  101 FORMAT (20H CONVERGENCE FAILURE)
      GO TO 100
  120 PRINT 1001
 1001 FORMAT (16H MATRIX SINGULAR)
  100 FIS1 = IS-1
      DO 150 I = 1,IR
      SUM = 0.0
      DO 140 J = 1,IS
  140 SUM = SUM+D(J,I)**2
  150 E(I) = SQRTF(RRQ/(SUM*FIS1))
      RETURN
      END
```

```
C
      SUBROUTINE   GAUSS3(N,EP,A,X,KER)
      DIMENSION A(10,10), X(10,10)
      DO 1 I=1,N
      DO 1 J=1,N
    1 X(I,J)=0.0
      DO 2 K=1,N
    2 X(K,K)=1.0
   10 DO 34 L=1,N
      KP=
      Z=0.0
      DO 12 K=L,N
      IF(Z-ABSF(A(K,L)))11,12,12
   11 Z=ABSF(A(K,L))
      KP=K
   12 CONTINUE
      IF(L-KP)13,20,20
   13 DO 14 J=L,N
      Z=A(L,J)
      A(L,J)=A(KP,J)
   14 A(KP,J)=Z
      DO 15 J=1,N
      Z=X(L,J)
      X(L,J)=X(KP,J)
   15 X(KP,J)=Z
   20 IF(ABSF(A(L,L))-EP)50,50,30
   30 IF(L-N)31,34,34
   31 LP1=L+1
      DO 36 K=LP1,N
      IF(A(K,L))32,36,32
   32 RATIO=A(K,L)/A(L,L)
      DO 33 J=LP1,N
   33 A(K,J)=A(K,J)-RATIO*A(L,J)
      DO 35 J=1,N
   35 X(K,J)=X(K,J)-RATIO*X(L,J)
   36 CONTINUE
```

```
   34 CONTINUE
   40 DO 43 I=1,N
      II=N+1-I
      DO 43 J=1,N
      S=0.0
      IF(II-N)41,43,43
   41 IIP1=II+1
      DO 42 K=IIP1,N
   42 S=S A(II,K)*X(K,J)
   43 X(II,J)=(X(II,J)-S)/A(II,II)
      KER=1
      RETURN
   50 KER=2
      RETURN
      END
C
      FUNCTION EQN(A,X,XB,XC,NOF)
      DIMENSION A(10)
      IF (A(3)*X-300.) 1,2,2
    1 EQN=A(1)+A(2)*(1.-EXPF(-A(3)*X))+A(4)*X
      GO TO 3
    2 EQN=A(1)+A(2)+A(4)*X
    3 RETURN
      END
      END
  TEST    SAMPLE DATA   HOWARD, M.A.   PROGRAM CREEP
 4 28 1  1     1.0E-4
3AD15      24.9       .144       .131       16.52
     1. E-05        1.0E-05         1.0E 5        1.0E-05
    15. E-03      20.0E-03          1.0E        20.0E-05
  110  12   128  131  138  142  145  150  158  162  175  184  192  198        1
  210  228  255  272  285  315  335  365  390  417  452  470  513  563        2
        56        139        278        417        556        694        833   01
      1111      1388       1667        25       3333       4167        5      02
      6667        1       18333     26667       35          6         85      04
   135        19667      28833      48833      61333       11        235167   05
```

```
..JOB0630,HOWARD MA
      PROGRAM CREEPDRW
C   PROGRAM IS USED TO COMPARE TWO SETS OF DATA WITH THE FITTED EQUATION.
C   TMAX IS MAX VALUE OF TIME, IS AND IT ARE NO. OF POINTS IN RESPECTIVE DATA.
C   A AND B ARE PARAMETERS FOUND FOR TWO SETS OF DATA IN PROGRAM CREEP.
C   PT AND QT ARE ELONGATION DATA FOR TWO SETS OF DATA.  PX AND QX ARE TIME
C   DATA CORRESPONDING TO PT AND QT RESPECTIVELY.  CONST SERVES ONLY TO SIMPLIFY
C   INPUT AND FOR TEST DATA EQUALS 1000.
C   ITITLE AND OTHER ARGUMENTS OF DRAW SUBROUTINE ARE FOUND IN J7-NPS-DRAW.
      DIMENSION A(4),B(4),ITITLE(12),PT(90),QT(90),PX(90),
     1QX(90),P(30),Q(30),U(30),V(30),YA(200),YB(200),T(200)
      READ 21,TMAX,IS,IT,CONST
      READ 22,(A(I),I=1,4)
      READ 22,(B(I),I=1,4)
      READ 23,(PT(I),I=1,IS)
      READ 24,(PX(I),I=1,IS)
      READ 23,(QT(I),I=1,IT)
      READ 24,(QX(I),I=1,IT)
   21 FORMAT (1F5.0,2I5,1F10.0)
   22 FORMAT(4E14.2)
   23 FORMAT(14F5.1)
   24 FORMAT(7F10.5)
   25 FORMAT(I3)
   26 FORMAT (4E14.3)
      PRINT 26,A,B
      DO 1 I=1,IS
      PT(I)=PT(I)/CONST
    1 CONTINUE
      DO 2 I=1,IT
      QT(I)=QT(I)/CONST
    2 CONTINUE
      R=TMAX/200.
      T(1)=0.0
      DO 3 I=2,200
      T(I)=T(I-1)+R
    3 CONTINUE
```

```
      DO 4 I=1,200
      YA(I)=EQN(A,T(I))
    4 CONTINUE
      DO 5 I=1,200
      YB(I)=EQN(B,T(I))
    5 CONTINUE
      IF(30-IS)6,8,8
    6 DO 7 I=1,30
      P(I)=PT(2*I-1)
      W(I)=PX(2*I-1)
    7 CONTINUE
      GO TO 10
    8 DO 9 I=1,IS
      P(I)=PT(I)
      W(I)=PX(I)
    9 CONTINUE
   10 IF(30-IT)11,13,13
   11 DO 12 I=1,30
      Q(I)=QT(2*I-1)
      V(I)=QX(2*I-1)
   12 CONTINUE
      GO TO 15
   13 DO 14 I=1,IT
      Q(I)=QT(I)
      V(I)=QX(I)
   14 CONTINUE
   15 DO 16 I=1,12
      ITITLE(I)=8H
   16 CONTINUE
      LABEL= 4H S=
      ITITLE(1)=8H HOWARD
      ITITLE(2)=8HMA
      ITITLE(7)=8H CREEP O
      ITITLE(8)=8HF PE/PP
      ITITLE(9)=8H SIX
      CALL DRAW(200,YA,T,1,0,LABEL,ITITLE,0.,0.,0,0,0,0,8,15,1,LAST)
```

```
      PRINT 25, LAST
      CALL DRAW(200,YB,T,2,0,LABEL,ITITLE,0.,0.,0,0,0,0,8,15,1,LAST)
      PRINT 25, LAST
      LABEL=8H
      CALL DRAW(30,P,U,2,1,LABEL,ITITLE, .,0.,0,0,0,0,8,15,1,LAST)
      PRINT 25, LAST
      CALL DRAW(30,Q,V,3,2,LABEL,ITITLE, .,0.,0,0,0,0,8,15,1,LAST)
      PRINT 25,LAST
      END
      FUNCTION EQN(A,X)
      DIMENSION A(4)
      IF(A(3)*X-300.)1,2,2
    1 EQN=A(1)+A(2)*(1.-EXPF(-A(3)*X))+A(4)*X
      GO TO 3
    2 EQN=A(1)+A(2)+A(4)*X
    3 RETURN
      END
      END

C   TEST   SAMPLE DATA   HOWARD M. A.    PROGRAM CREEPDRW
    83    28    28        1000
      22.82E-03        31.93E-03          .96E         23.83E-05                  3AG15
      19.37E-03        29.46E-03          .98E         21.65E-05                  3AF15
   278  298  315  328  345  368  392  427  452  478  517  534  575  628              18
   631  639  648  657  681  686  693  697  710  714  716  720  724  726              19
       6667       1        16667      21667       3        46667      71667         031
     12167      18333       275        475        6        10867      23383         032
     247167     27133      299167     32333     472167     4905       53883         033
     57133      687        7065       72733     76833      797167     82383         034
   241  258  280  298  310  320  342  361  388  410  432  464  480  518              10
   563  567  574  582  589  608  613  620  624  636  639  641  647  649              11
       6667       1        18333      26667      35        43333      68333         017
      93333     14333       205       29667     49667      62167      11083         018
     236        24933      2735       30133     3255       47433      49267         019
     541        5735       689167     70867     7295       7705       79933         020
```

APPENDIX C

SPECIAL EQUIPMENT

Viscoelastic studies of materials require many sets of data with long time scale measurements. This necessitates the availability of many independently operated measuring devices. This requirement led to the design and construction of additional Creep machines operated by a simple lever arm device for loading and a series of ball and socket swivels with turnbuckles for varying the length and size of specimens used. Figures 39 through 42 are pictures and drawings of the constant load Creep machines designed and built in this project.

Additionally, since stress relaxation measurements are necessary in characterizing the viscoelastic properties of materials, a multiple capacity stress relaxation (constant strain) machine was designed. This machine is still in the design and construction stages. Figure 43 is a drawing of the machine.

A necessary item in the measurement of creep and relaxation data is the measuring device and recording equipment. The potential advantages of automatic recording of electrical signals made it desirable to use conventional wire strain gauges. However, their very limited extension capability and the requirement of attaching them to the specimen made it necessary to fabricate a special fixture to increase their extension capability. Figure 44 is a schematic of the clip-on electromechanical extensometer devised. It consists of a phosphor bronze blank, bent to the dimensions seen, with two BLH SR-4 type A-5-1 strain gauges attached as shown in Figure 45. The use of a simple aluminum frame and rubber bands serve to clip the extensometer to the specimen as shown in Figures 46 and 47. The attached strain gauges serve as one-

half of a Wheatstone bridge and when connected as seen in Figure 48, can be calibrated to give a signal proportional to the strain in the specimen. The relationship between the strain at the center of the face of the clip gauge and the elongation between the feet of the clip gauge is seen in the following analysis.

Figure 49 is a schematic drawing of the blank used in the clip gauge. Marin and Sauer [12] show that the total axial strain on the blank is:

$$(1) \qquad \delta = \left[\frac{Hh}{EI}\right]\left[\frac{2}{3} + \frac{L}{h} + \left(\frac{L}{h^3}\right)\frac{I}{A}\right]$$

where A = cross-sectional area of the blank (bd)

I = moment of inertia of the area ($bd^3/12$)

E = modulus of elasticity in the blank.

The unit strains at point P (where the SR-4 strain gauges are centered) are:

$$(2) \qquad \varepsilon_1 = -\varepsilon_2 = \frac{1}{E}\left[\frac{H}{A} \pm \frac{6M}{bd^2}\right] \quad \text{or} \quad \frac{H}{Ebd}\left(1 \pm \frac{h}{d}\right)$$

Placing the value of H from Equation 1 into Equation 2, gives the following relation:

$$(3) \qquad \varepsilon_1 = -\varepsilon_2 = \left(\frac{\delta}{h}\right)\frac{\left(\frac{d}{h}\right)^2\left(1 \pm \frac{h}{d}\right)}{8 + 12\frac{L}{h} + \left(\frac{L}{h}\right)\left(\frac{d}{h}\right)^2}$$

If the strain gauges are placed in series as in the Wheatstone bridge, the measured strain is given by:

$$(4) \qquad \varepsilon = \varepsilon_1 - \varepsilon_2 = 2|\varepsilon_1| \propto \delta$$

The completed clip type extensometer was tested for linearity and hysterisis on a device similar to Figure 50. The calibration curve is shown in Figure 51. A modification of PROGRAM CREEP given in Appendix B will readily convert the mv output of the Wheatstone bridge into strain in inches per inch. A simple block diagram of the complete recording

system for Creep data is given in Figure 52. A similar diagram for the control and recording system of the Stress Relaxation machine is given in Figure 53.

FI[illegible] 39 CREEP LABORATORY

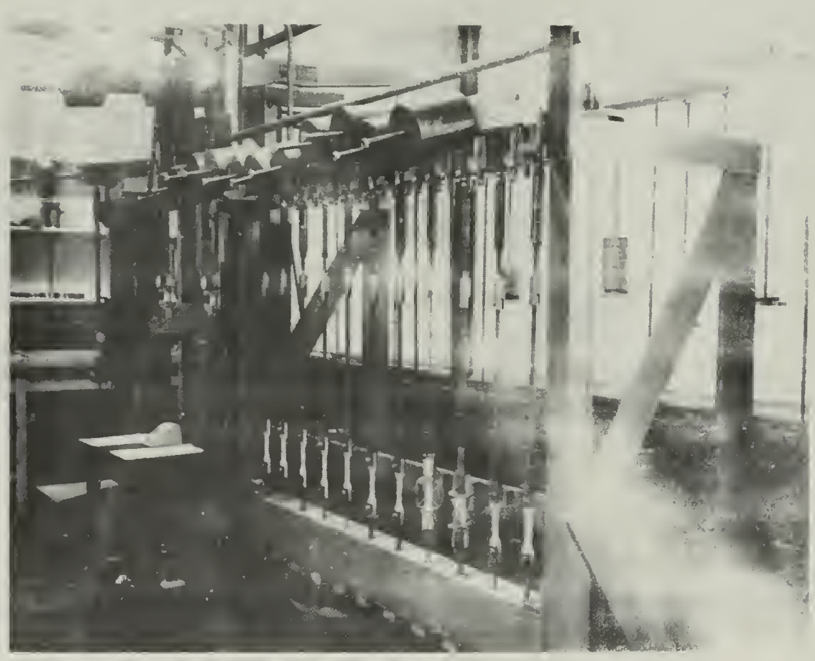

FIGURE 40 ELEVEN UNIT CREEP MA[illegible]

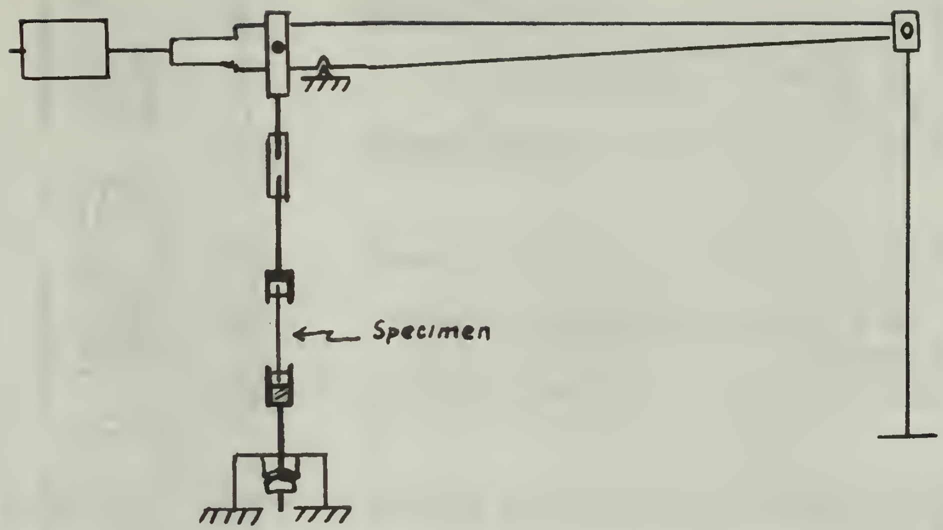

FIGURE 41 LEVER ARM ASSEMBLY

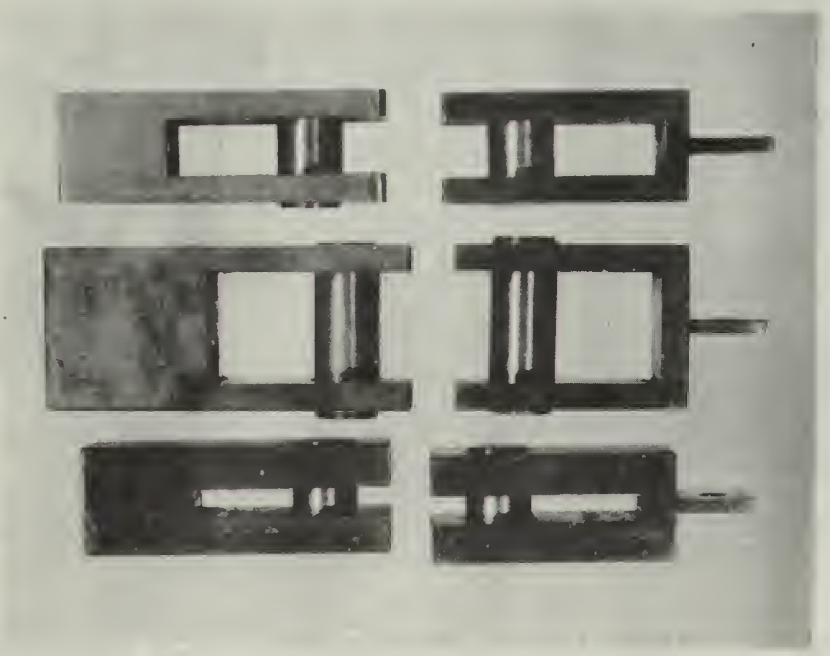

FIGURE 42 VARIOUS SPECIMEN HOLDERS

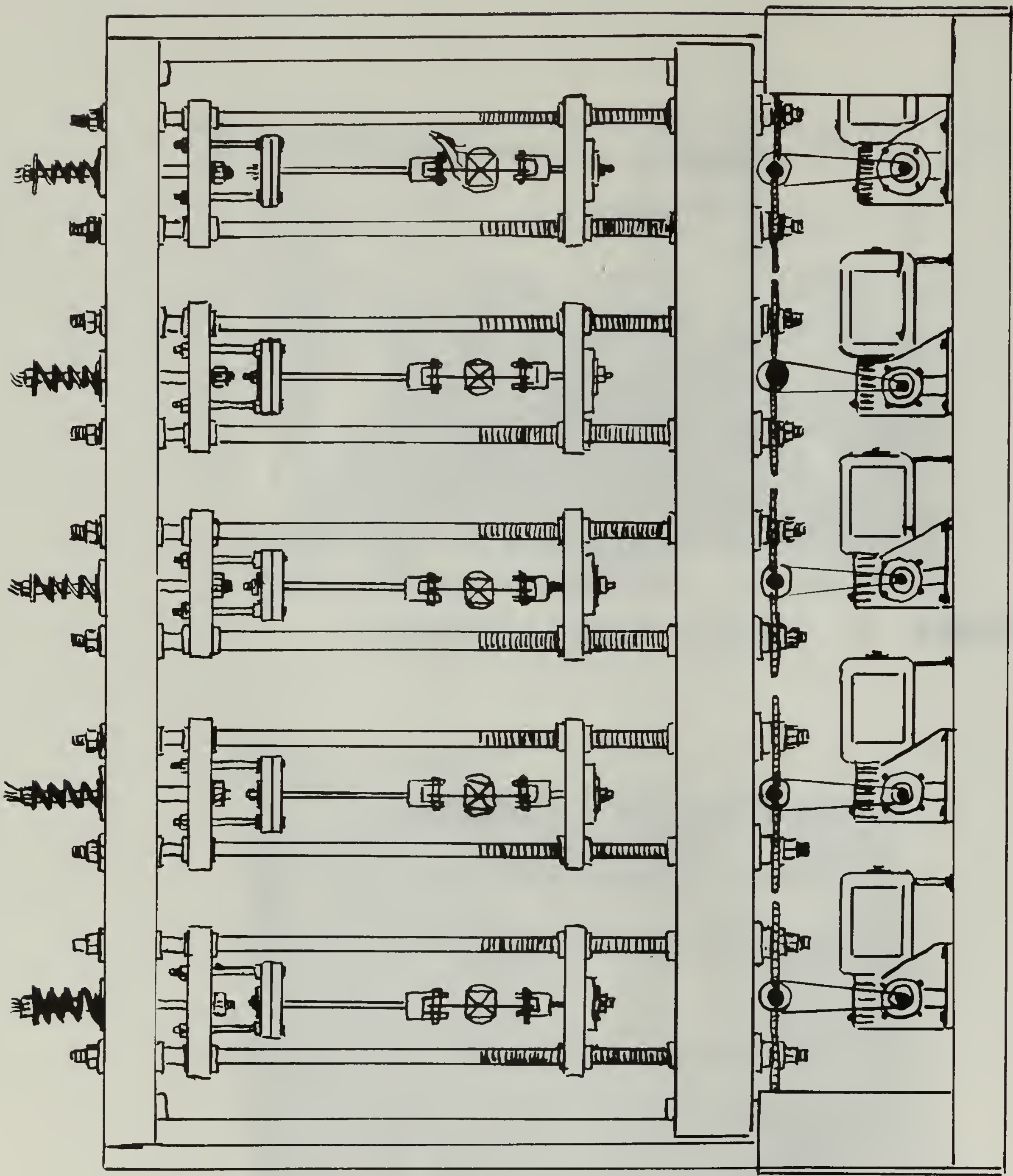

FIGURE 43 FIVE UNIT STRESS RELAXATION MACHINE

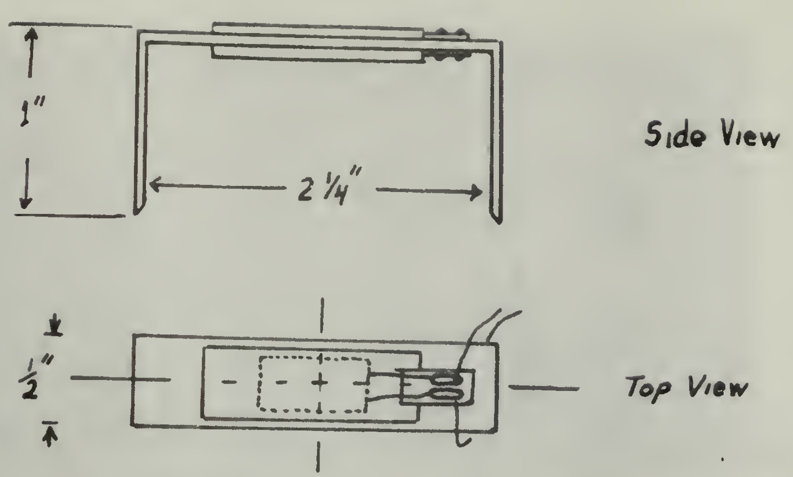

FIGURE 44 CLIP GAUGE EXTENSOMETER
(DIMENSIONS)

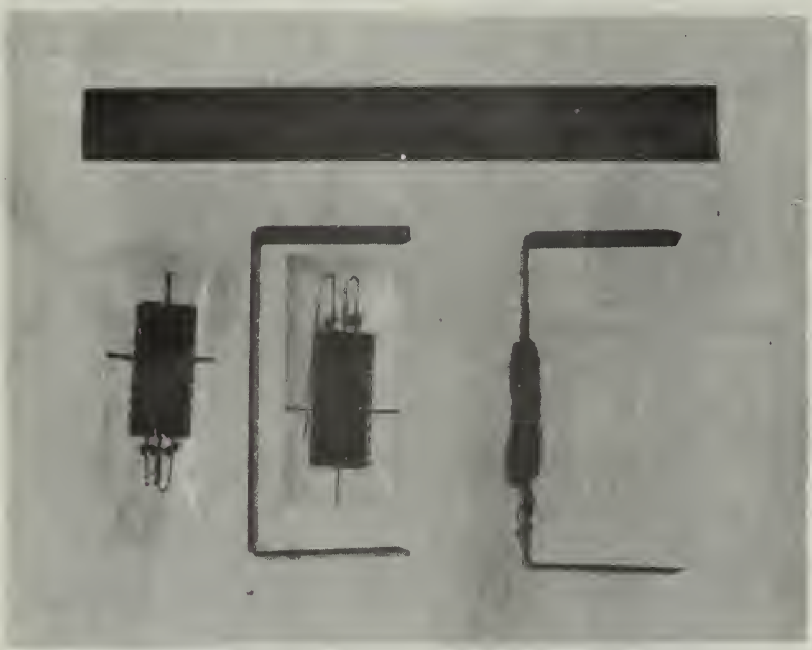

FIGURE 45 CLIP GAUGE EXTENSOMETER
(COMPONENTS)

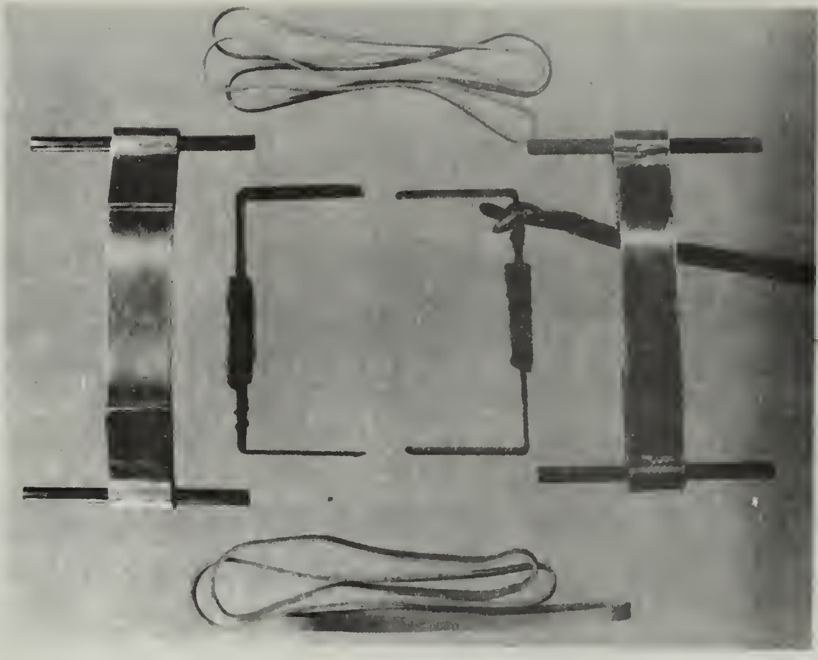

FIGURE 46 CLIP GAUGE EXTENSOMETERS & BRACKETS

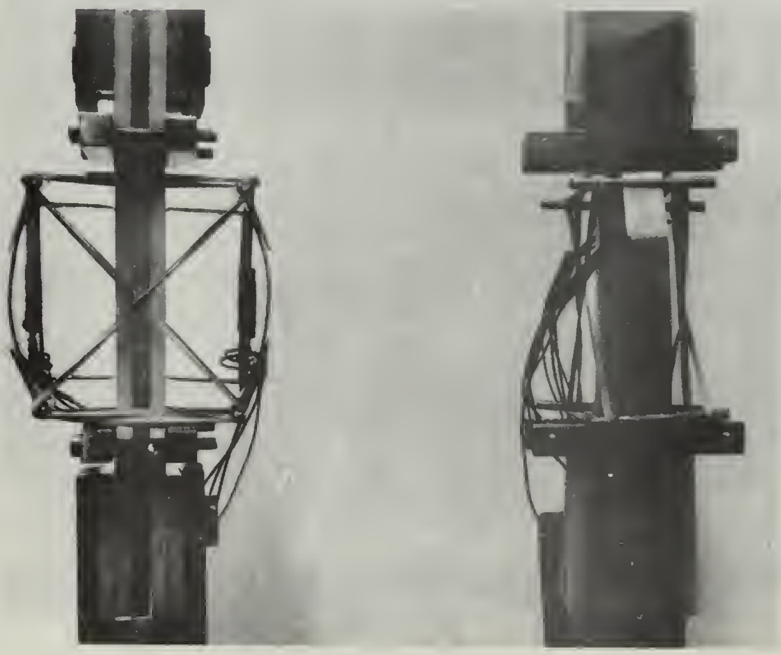

FIGURE 47 CLIP GAUGE EXTENSOMETER ATTACHED TO SPECIMEN

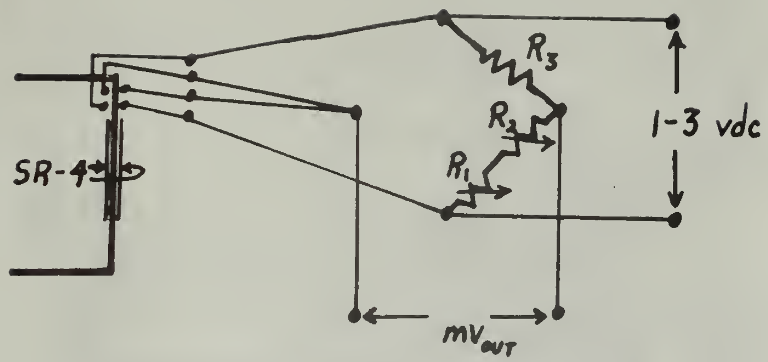

FIGURE 48 CLIP GAUGE EXTENSOMETER WHEATSTONE BRIDGE CIRCUITRY

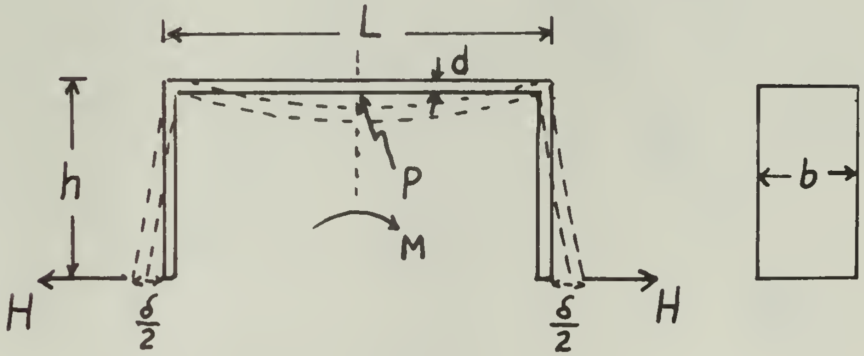

FIGURE 49 CLIP GAUGE EXTENSOMETER THEORETICAL ANALYSIS SCHEMATIC

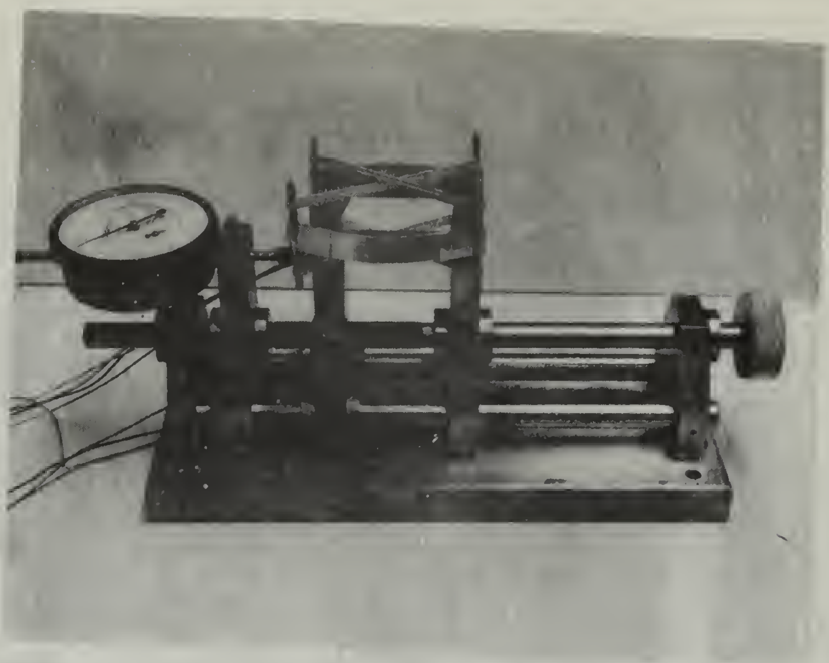

FIGURE 50 EXTENSOMETER CALIBRATION DEVICE

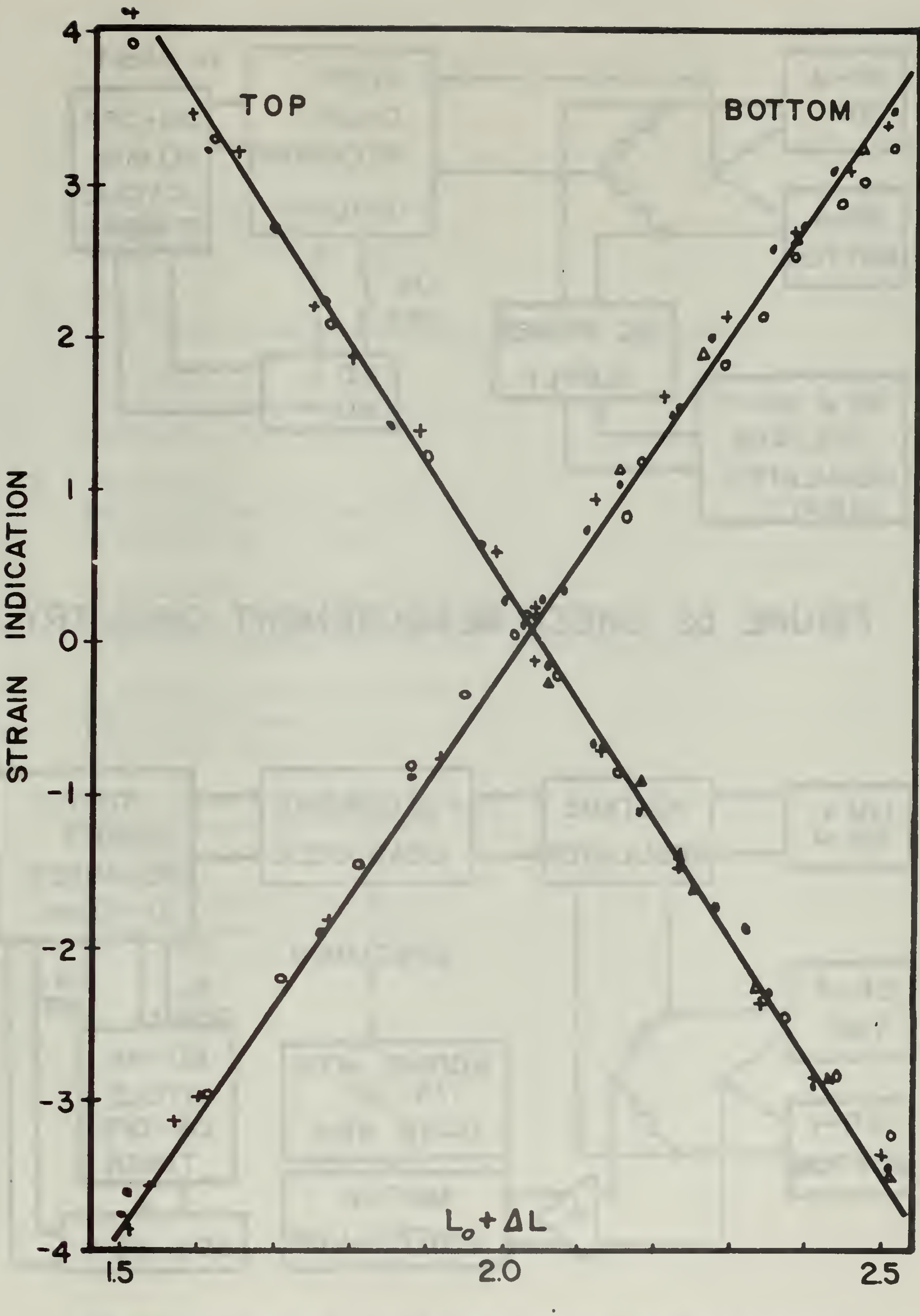

FIGURE 51 CLIP GAUGE EXTENSOMETER CALIBRATION CURVE

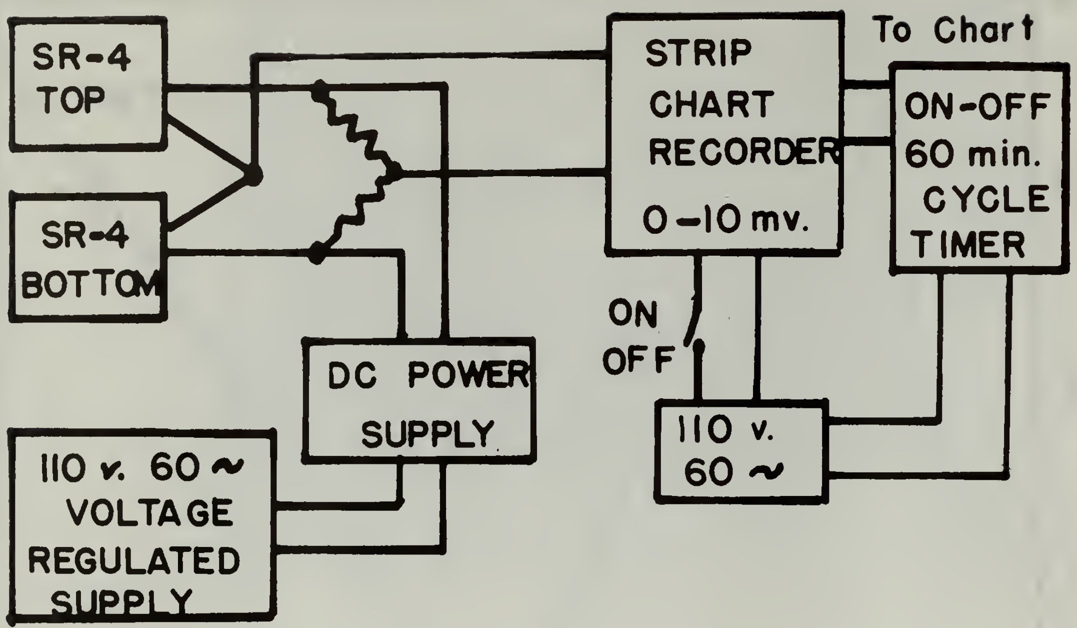

FIGURE 52 CREEP MEASUREMENT CIRCUITRY

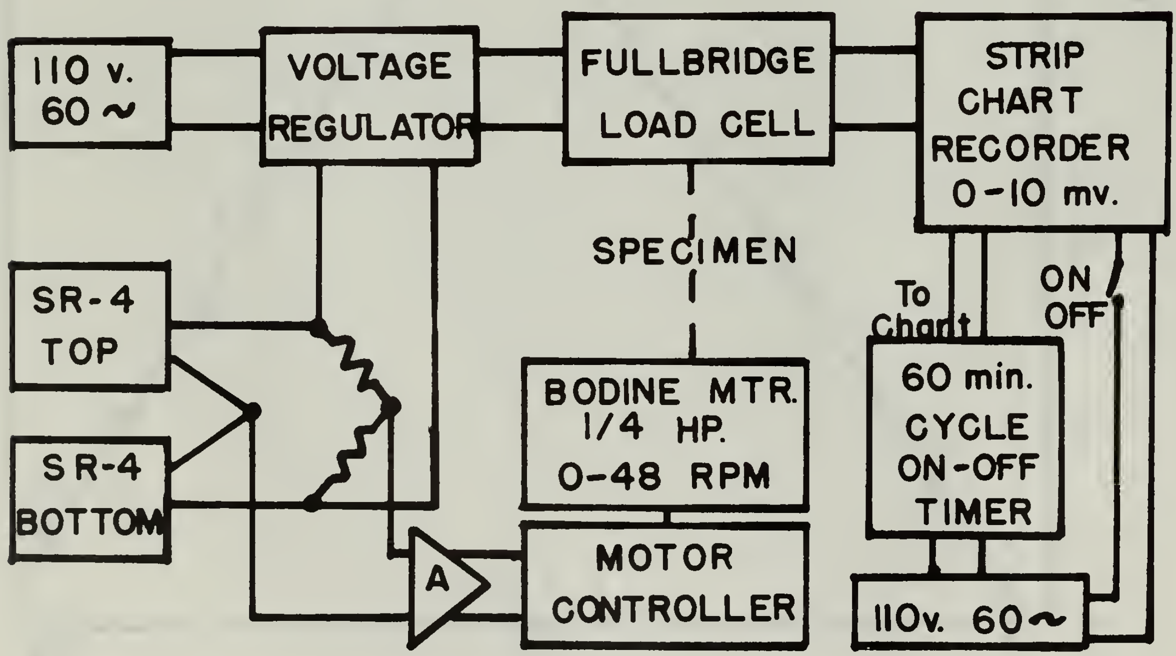

FIGURE 53 RELAXATION MEASUREMENT CIRCUITRY

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13. ABSTRACT

An investigation of uniaxial creep in simple synthetic composites of polyethylene and polypropylene was made to determine the parametric behavior and interrelation of each component by varying the relative volume and interfacial contact area. A mathematical model was developed and used to predict the experimental behavior which was determined by least squares fitting of the data. A digital computer was used in the analysis and good correlation between the experimental measurements and theoretical predictions was obtained. Included is a report of the design and construction of equipment for theoretically meaningful viscoelastic measurements.

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POLYPROPYLENE						
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